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Application of Flux-Corrected Transport to TTCP Joint Launch Blast Computational Effort

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Laboratory for Computational Physics

December 31, 1985

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Washington, D.C.

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A general-purpose Flux-Corrected Transport (FCT) hydrocode has been used to treat two muzzle blast test problems. Analysis of the results and comparison with data indicates that the results are physically realistic and, within the modeling assumptions, highly accurate. The FCT simulation model used runs on the Cray-1 and on smaller mainframe computers including the VAX and the multitasking array processors in our Graphical and Array Processing System.

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APPLICATION OF FLUX-CORRECTED TRANSPORT TO TTCP
JOINT LAUNCH BLAST COMPUTATIONAL EFFORT

INTRODUCTION

The method of Flux-Corrected Transport (FCT) was developed about ten
years ago (Boris and Book, 1973; Book et al., 1975; Boris and Book, 1976) as
a means for solving systems of hyperbolic equations in such a way that
physically positive quantities like mass and energy density remain positive.
Its principal application has been to compressible fluids, i.e., fluids in
which some of the flow speeds are comparable with or greater than the local
speed of propagation of waves in the medium. Examples include plasmas,
combusting systems, and gas-dynamic flows. Applications of FCT to muzzle
blast problems were first made by Townend and Edwards (1982).

During the past decade the method has been extended and generalized in a
number of important respects. These include the construction of general-
purpose algorithms for solving fluid equations on moving nonuniform grids in
a curvilinear coordinate system (Boris 1976), strictly multidimensional FCT
algorithms (as opposed to timestep-splitting of one-dimensional algorithms,
Zalesak 1979), and variants on these. In addition, numerous techniques have
been developed by other workers which incorporate the positivity-preserving
property in other ways (Harten, 1978; Van Leer, 1979; Collela and Woodward,
1984). The weight of opinion among computational scientists who deal with
problems of compressible flow now strongly affirms the superiority of
positivity-preserving methods (e.g., Total Variation Diminshing or TVD) over
conventional ones. The advantages are improved robustness, flexibility,
resolution, and freedom from nonphysical numerical artifacts.

FAST2D (Boris 1976) is an FCT code for solving the two-dimensional fluid equations in Cartesian or r-z geometry. It employs timestep-splitting to permit the use of JPBFCT, a general-purpose one-dimensional convective equation solver for both coordinate sweeps in all of the fluid equations.

To explain what this means, let us describe a class of FCT algorithms which includes JPBFCT as a particular case. To advance the one-dimensional continuity equation

$$\frac{\partial \rho}{\partial t} = - \frac{\partial}{\partial x} (\rho v) \tag{1}$$

one timestep on a uniform mesh with a given flow velocity v, we suppose the old cell-centered values ρ_j^O and v_j are known. A three-point conservative finite-difference operator acting on ρ_j^O can be written in the form

$$\rho_j^T = \rho_j^O - \varepsilon_{j+1/2}\, \rho_{j+1/2} + \varepsilon_{j-1/2}\, \rho_{j-1/2} \, , \tag{2}$$

where $\rho_{j+1/2} = \frac{1}{2}(\rho_j + \rho_{j+1})$. To obtain a first-order approximation to Eq. (1), we must define $\varepsilon_{j+1/2}$ to be the Courant number $v_{j+1/2}\delta t/\delta x$, where $v_{j+1/2} = \frac{1}{2}(v_j + v_{j+1})$. In FCT a numerical diffusion is then applied to ρ_j^T in flux form according to

$$\rho_j^{TD} = \rho_j^T + \nu_{j+1/2}(\rho_{j+1}^O - \rho_j^O) - \nu_{j-1/2}(\rho_j^O - \rho_{j-1}^O) \, . \tag{3}$$

Next we act to eliminate this excess diffusion. If we simply applied another diffusion operation, this time with the opposite sign, it would cancel the diffusion terms already present in ρ_j^{TD}. Instead we define new densities ρ_j^n

$$\rho_j^n = \rho_j^{TD} - \phi_{j+1/2}^c + \phi_{j-1/2}^c, \tag{4}$$

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where the "corrected" fluxes $\phi^c_{j+1/2}$ differ from the "raw" fluxes $\phi_{j+1/2} = \mu_{j+1/2} (\rho^o_{j+1} - \rho^o_j)$ in two ways: we use $\{\rho^T_j\}$ instead of $\{\rho^o_j\}$ in the definition of the raw fluxes (this allows us to optimize some property in the difference scheme, as will be seen shortly); and we correct the fluxes, so that the antidiffusion process (which evidently tends to make all gradients steeper) can enhance no extrema already present in $\{\rho^{TD}_j\}$, nor introduce any new ones. The simplest formula for achieving this in all possible situations is that used in "strong flux limiting":

$$\phi^c_{j+1/2} = S \cdot \{\max[0, \min (|\phi_{j+1/2}|, \Delta_{j-1/2}, \Delta_{j+3/2})]\} , \qquad (5)$$

where $S = \text{sign } \phi_{j+1/2}$ and $\Delta_{j+1/2} = \rho^{TD}_{j+1} - \rho^{TD}_j$.

At most points in a gently varying profile no correction is required and $\phi^c_{j+1/2} = \phi_{j+1/2}$. In that case we can perform a Von Neumann analysis, calculating the complex propagator or amplification factor $A = A_r + iA_i = \rho^n_j/\rho^o_j$ for a sinusoidal density profile $\rho^o_j = \exp(ijk \, \delta x)$, where k is the wave number. Writing $\beta = k\delta x$ and $\varepsilon = v\delta t/\delta x$, we expand the amplification in powers of β

$$A = 1 + A_2 \, \beta^2 + A_4 \, \beta^4 + \ldots \qquad (6)$$

and the relative phase error

$$R = \frac{1}{\beta\varepsilon} \tan^{-1} (A_i/A_r) - 1 = R_2 \, \beta^2 + R_4 \, \beta^4 + \ldots . \qquad (7)$$

It is easy to show that the condition that A_2 vanish is

$$\nu - \mu = \frac{1}{2} \varepsilon^2 . \qquad (8)$$

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The condition that R_2 vanish is

$$\mu = \frac{1}{6} - \frac{1}{6}\epsilon^2 .$$

(9)

While other choices of ν and μ are possible, Eqs. (8) and (9) lead to the most useful general-purpose algorithm within this class and have been used in a wide variety of supersonic flow problems. Besides producing small phase and amplitude errors, as shown above, this choice of the diffusion and antidiffusion coefficients ν and μ treats shocks very accurately, unlike schemes where ν and μ are small.

Generalizing this scheme to handle the momentum and energy equations presents no problem as the treatment of the driving terms $-\nabla p$, etc., and $-\nabla \cdot p v$ is not very sensitive. Extension to nonuniform meshes and curvilinear geometry is also straightforward. When fully vectorized and optimized for a particular machine (in the present case, the Cray-1) it runs at about 2 μs per zone per timestep per equation per coordinate direction.

RESULTS

Case I: Flow From the Open End of a Shock Tube

Figure 1 reproduces the BRL drawings defining the geometry of the shock tube and prescribing the computational domain to be used (Schmidt, 1985). Although it would be of interest to model the entire length of the shock tube (including the 0.673 m driver section and the whole 3.044 m driven section), this would necessitate a calculation with a computational region approximately ten times as long as that specified for the case. In our calculation we used a grid with 200 zones in the radial and 400 zones in the axial direction, with mesh sizes $\Delta r = \Delta z = 0.228$ cm. Although temperature and density do not deviate too widely from standard conditions and $\gamma = 1.4$

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holds approximately, we used a real-air equation of state. Reflecting
boundary conditions were employed at r = 0, and outflow conditions (valid for
supersonic flow) at maximum radial and axial displacement. The conditions at
z = 0 were maintained at their initial values, which is valid until
disturbances propagating out of the driver region reach the computational
domain.

Timesteps were limited to 0.5 times the value imposed by the Courant
condition and averaged about a microsecond. The calculation ran 1618 cycles,
with dumps being obtained at times t = 0.025, 0.05, 0.1, 0.2, 0.5, 1.0 and
1.5 ms. Using these dumps we generated velocity vector plots and contours of
constant density, pressure, and Mach number. In addition, time histories of
pressure, density, and Mach number were generated at stations situated at a
distance of 1.5 times the tube diameter D = 0.152 m from the center of the
tube exit along the 0, 30, 60, 90, 120, 130, and 138.2 degree rays. These
locations are indicated by the dots in Fig. 1c. Since the station along the
0° ray was of particular interest in connection with determining the
location of the backward-facing shock, ten additional stations were located
in the neighborhood of the station along this ray.

Figures 2-8 show the overall flow at the plotting times specified above.
In each figure we have four plots: contours of (a) pressure, (b) density,
and (c) Mach number; and (d) velocity vector plots. Note that by 0.5 ms
(Fig. 6) several well-defined gasdynamic discontinuities have developed.
These include a disk-shaped backward-facing shock which terminates at its
outer radius in a compression fan. The latter is rolled up into a vortex
ring. At a radius of approximately 0.05 m a cylindrical slip surface (which
shows up as a discontinuity in density but not pressure) intersects this
shock, producing a kink. By 1.5 ms (Fig. 8), when the primary shock has

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reached the end of the mesh, the vortex ring has expanded out to about 0.1 m in radius.

Figures 9 - 16 are station plots, each showing (a) overpressure, (b) density, and (c) Mach number at the prescribed locations. The flow behind the shock is of course subsonic everywhere. All stations show a pressure (and density) peak at shock arrival time, followed by a rarefaction wave. The stations located off the center line (all except no. 1) reach pressures less than ambient. Comparison with digitized traces of pressure measurements (Figs. 17 - 33) shows good agreement between calculated and recorded values except at station no. 1. There the calculated values (labelled with "A") are close to the measured ones (labelled with "B") until about 1 ms. Thereafter the latter peak up above the calculation by about 20 kPa and then drop below by about 60 kPa. We attribute this discrepancy to slight errors in defining the location of the backward-facing shock, probably caused by an increase in the effective flow velocity from the opening of the shock tube as a result of the formation of a boundary layer there. Rather than try to model this boundary layer, we introduced ten additional stations on the axis between 0.662 m and 0.683 m from the opening. The waveform which agrees best with the observed trace is that calculated at station no. 10 (Fig. 26, $y = 0.667$ m). Nevertheless, the unsteady behavior of the shock in the experimental setup precludes perfect agreement for these features.

Case II: 105 mm Muzzle Flow

In this problem the geometry is complicated by the addition of a baffle located downstream from the muzzle, and by the presence of the projectile at early times. No attempt was made to model the latter (although it is not difficult to do) because it has no influence on the flow near the muzzle

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except at very early times. Otherwise the same boundary conditions were used as in Case I.

The zone size was $\Delta r = \Delta z = 0.3$ cm. For this problem two fluid mass densities were propagated according to the continuity equation, using a single flow velocity field. One fluid, air, initially filled the entire grid outside the muzzle and the solid walls. The other fluid, representing detonation products from the propellant, expands out from the muzzle with the prescribed exit velocity of 1050 m/s. Partial pressures were obtained using respectively a real-air equation of state and a constant-gamma law ($\gamma = 1.25$) for the two fields.

Figures 34 - 38 shows contours of (a) pressure, (b) density, and (c) Mach number, and (d) velocity vector plots at the prescribed times t = 0.025, 0.05, 0.1, 0.5, and 1.0 ms, respectively. Note that by 0.1 ms part of the shock wave has reached the baffle and been deflected away. The central portion passes through the hole and begins to diffract around to the back of the baffle. By 0.5 ms the shock has left the top of the grid. Thereafter the solution quickly relaxes to a steady state, maintained by the propellant gases emerging from the howitzer muzzle.

Figures 39 - 47 show waveforms of (a) pressure, (b) density, and (c) Mach number at the nine prescribed stations. Stations (1) - (3), located on the front of the baffle, show slightly different peak values at shock arrival time and saturate at slightly different values at late times, reflecting their varying distances from the muzzle. The stations in front of, alongside, and behind the muzzle show variations which can readily be interpreted in terms of geometry. It is seen that although the flow is deflected by the baffle, beyond it (at distances $\gtrsim$ D) the baffle has little effect on most features in either contour or station plots.

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Since the flow is subsonic, the mesh boundaries should permit inflow of the surrounding ambient atmosphere at late times, and this should come to equilibrium with the emerging flow of propellent gases. Because we kept the same outflow boundary conditions as in Case I, inflow cannot take place, and at late times the pressures and densities near the outer boundary become unphysically low. For this reason we have plotted station histories only out to 1 ms.

CONCLUSION

We have carried out two test muzzle blast calculations using the FCT code FAST2D. Numerous simplifications have been introduced to minimize the programming effort required, and considerable improvement could be made in our treatment of (i) viscous boundary layers (in Case I); (ii) inflow and projectile boundary conditions (in Case II); and (iii) the propellant gas equation of state. Nevertheless, the agreement with the data in Case I and the physical plausibility and internal consistency of both cases strongly support the validity of this modeling approach and suggest that FCT hydrocodes can make a valuable contribution to the muzzle blast modeling effort.

Although the calculations described here were carried out on a Cray-1 supercomputer, it is worth noting that the computing requirements for FAST2D are actually very modest. The Laboratory for Computational Physics has assembled a Graphical and Array Processing System (GAPS) consisting of a VAX 11/780, two FPS 5305 array processors working in tandem (up to 10 APs are possible), an Aptec DPS 2400 I/O computer, and a Tektronix 4115B high-speed graphics device. This system is running a comparable two-dimensional hydrocode, programmed entirely in FORTRAN, at speeds of ~ 0.2 ms per mesh point per timestep, in either batch or interactive mode. In the latter it produces color plots of the evolving simulation approximately every 5 seconds with DICCMED hard copy capability. This is about 1/8 the speed of a single processor Cray X-MP. A sample frame from a muzzle blast calculation done using the RFM hydrocode on the GAPS is reproduced as Fig. 48. It is important to stress that such a system is small and can be maintained in a secure self-contained facility, where it can be dedicated entirely to muzzle blast or similar energetic gasdynamic calculations if so desired. The cost of the basic system is ~ $220K.

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SHOCK TUBE CONFIGURATION:

(a)
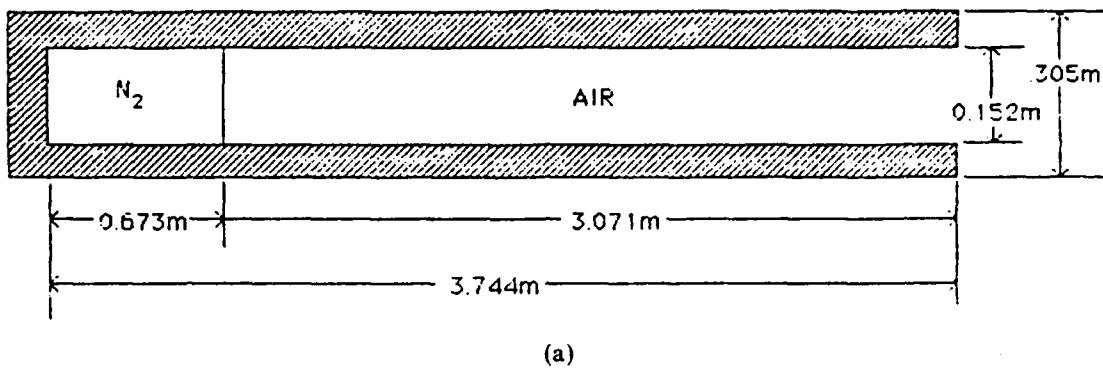
COMPUTATIONAL DOMAIN:

(b)

Figure 1

10
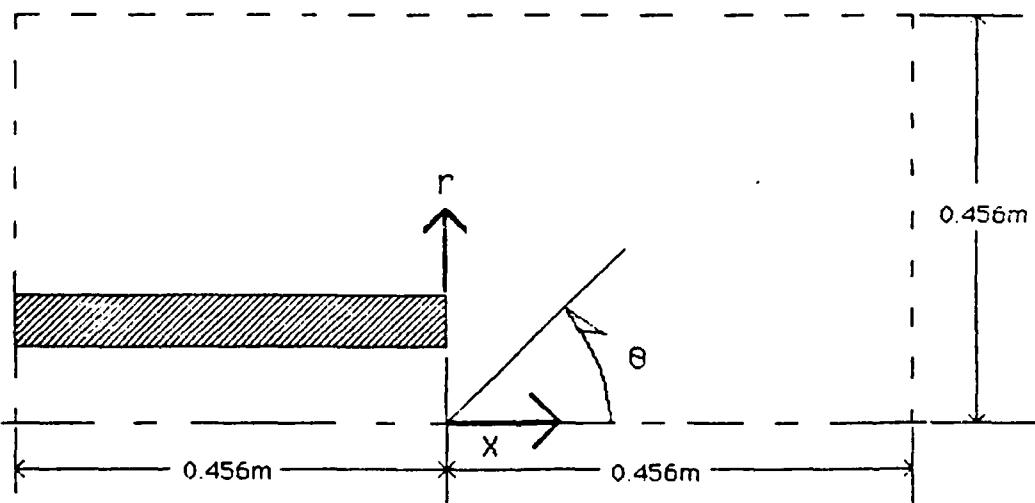
BLAST DIFFRACTION FROM SHOCK TUBE

TIME= 0.00000E+00 SEC.. STEP   1. DUMP TUBB0001   DENSITY 1. KG/M3
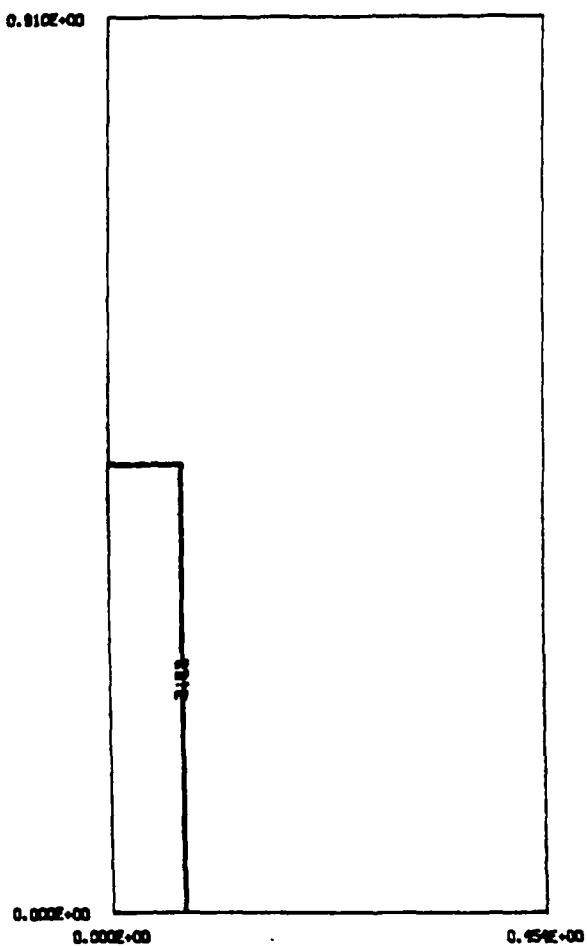
Figure 1b

BLAST DIFFRACTION FROM SHOCK TUBE

TIME= 0.00000E+00 SEC.. STEP   1. DUMP TUB80001   PRESSURE.NEWTONS/M**2

0.910E+00

0.000E+00

0.000E+00   0.154E+00
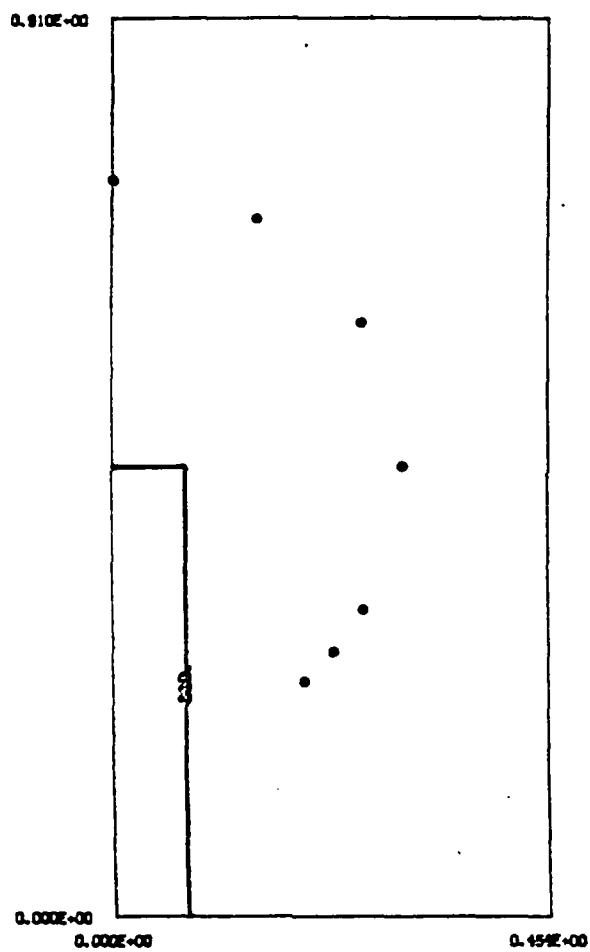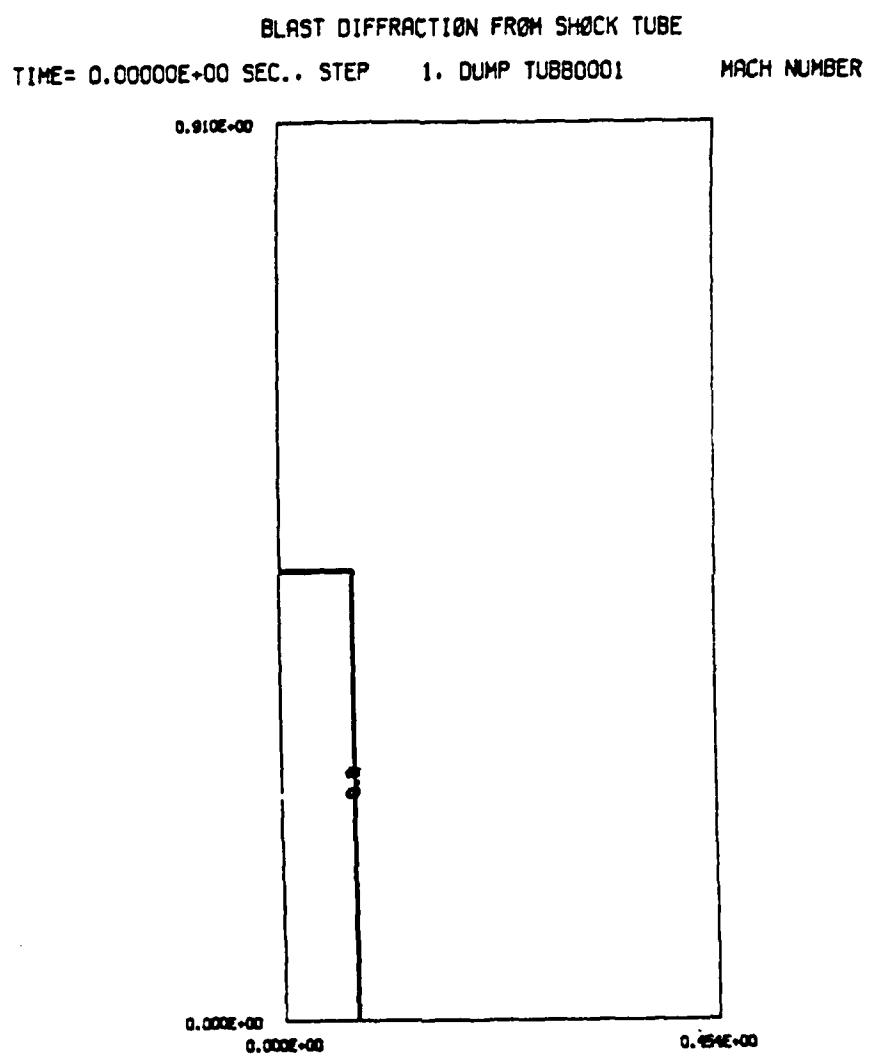
Figure 1c

BLAST DIFFRACTION FROM SHOCK TUBE

TIME= 0.00000E+00 SEC.. STEP   1. DUMP TUBB0001   MACH NUMBER

Figure 1c

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BLAST DIFFRACTION FROM SHOCK TUBE

TIME= 0.00000E+00 SEC.. STEP   1. DUMP TUBB0001   VELOCITY. M/SEC
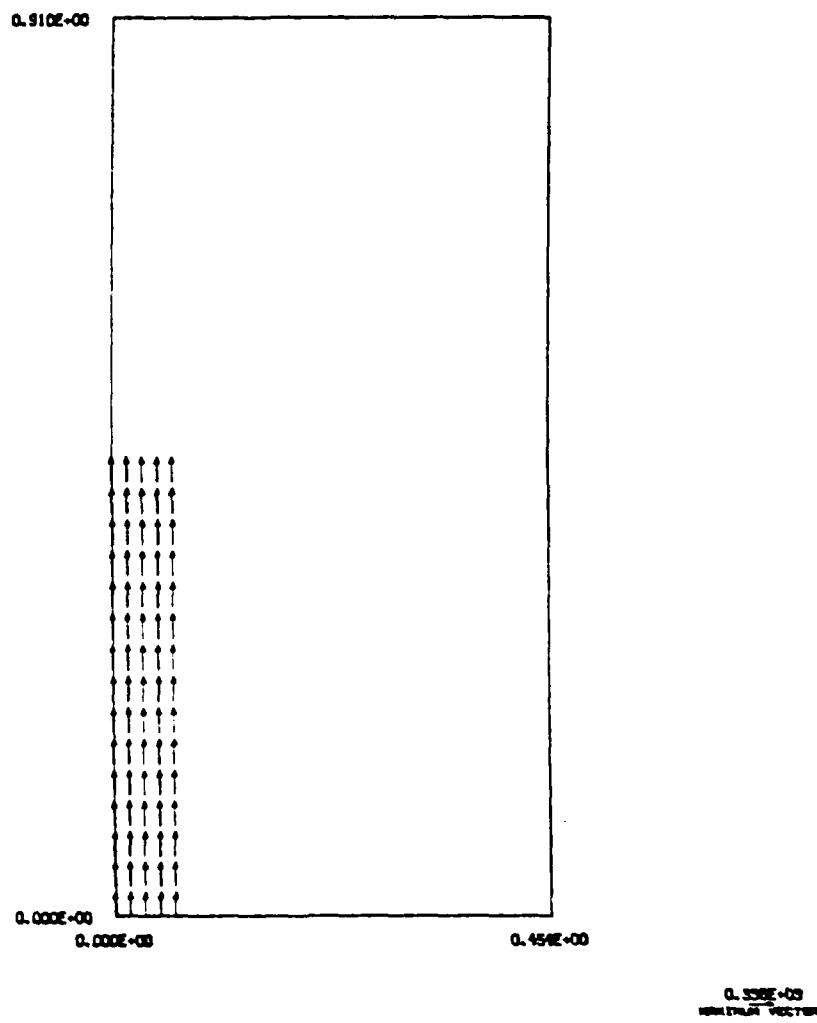
Figure 1d

BLAST DIFFRACTIØN FRØM SHØCK TUBE

TIME= 0.25649E-04 SEC.. STEP   86. DUMP TUBB0002   PRESSURE.NEWTØNS/M==2

Figure 2a

BLAST DIFFRACTION FROM SHOCK TUBE

TIME= 0.25649E-04 SEC., STEP   86. DUMP TUBB0002   DENSITY 1. KG/M3

Figure 2b

BLAST DIFFRACTIØN FRØM SHØCK TUBE

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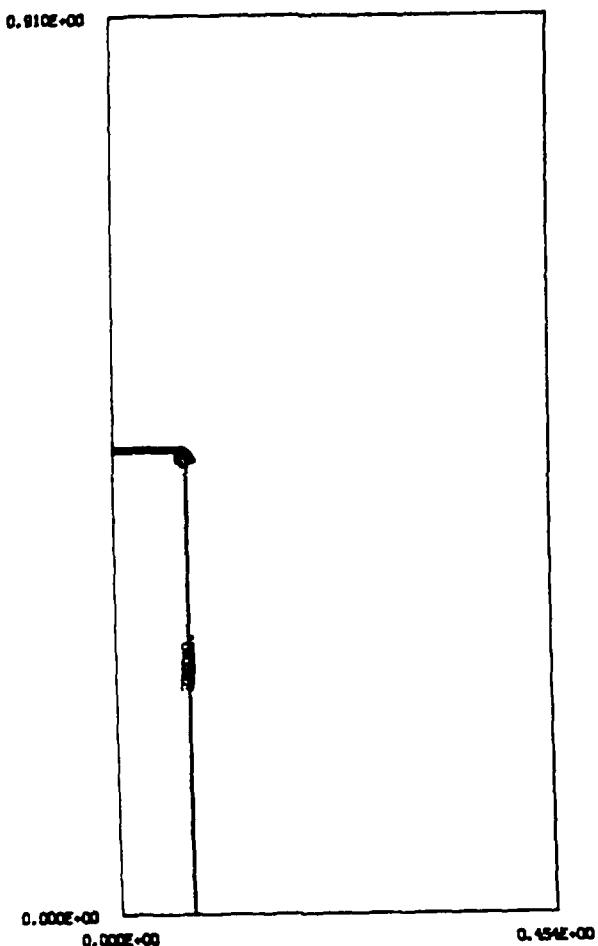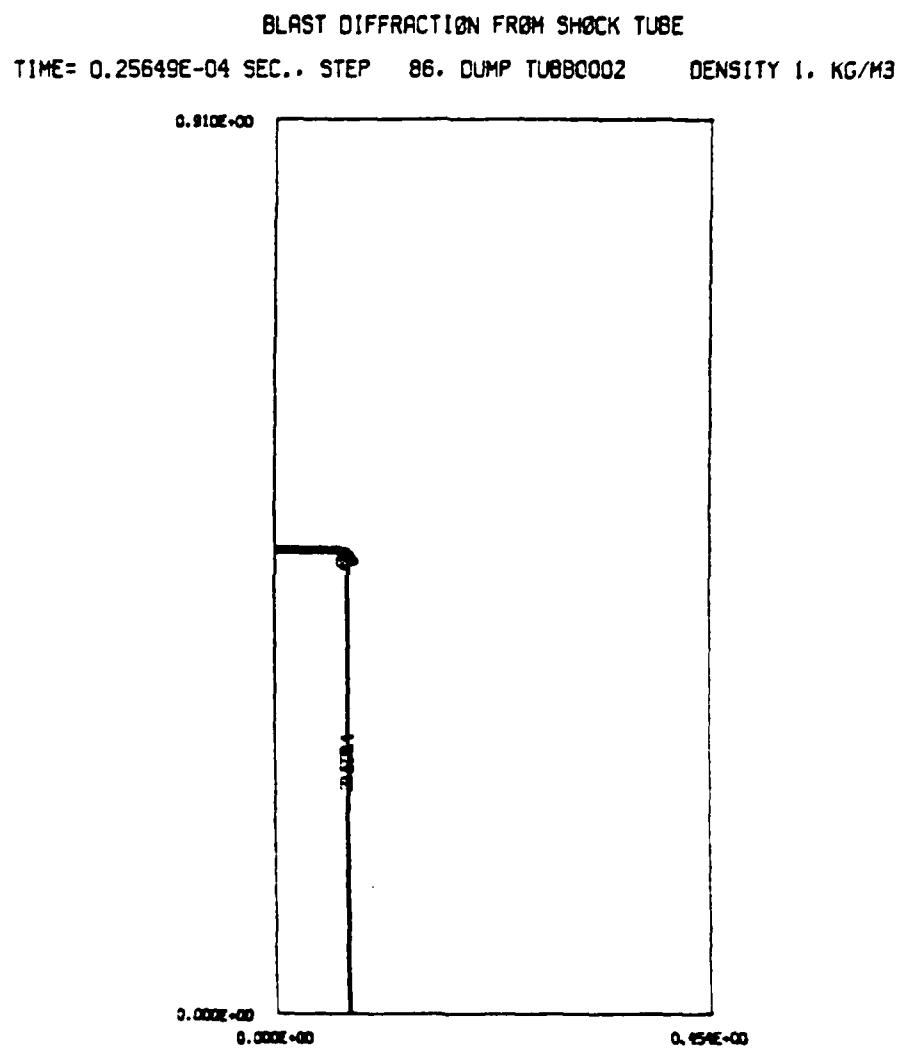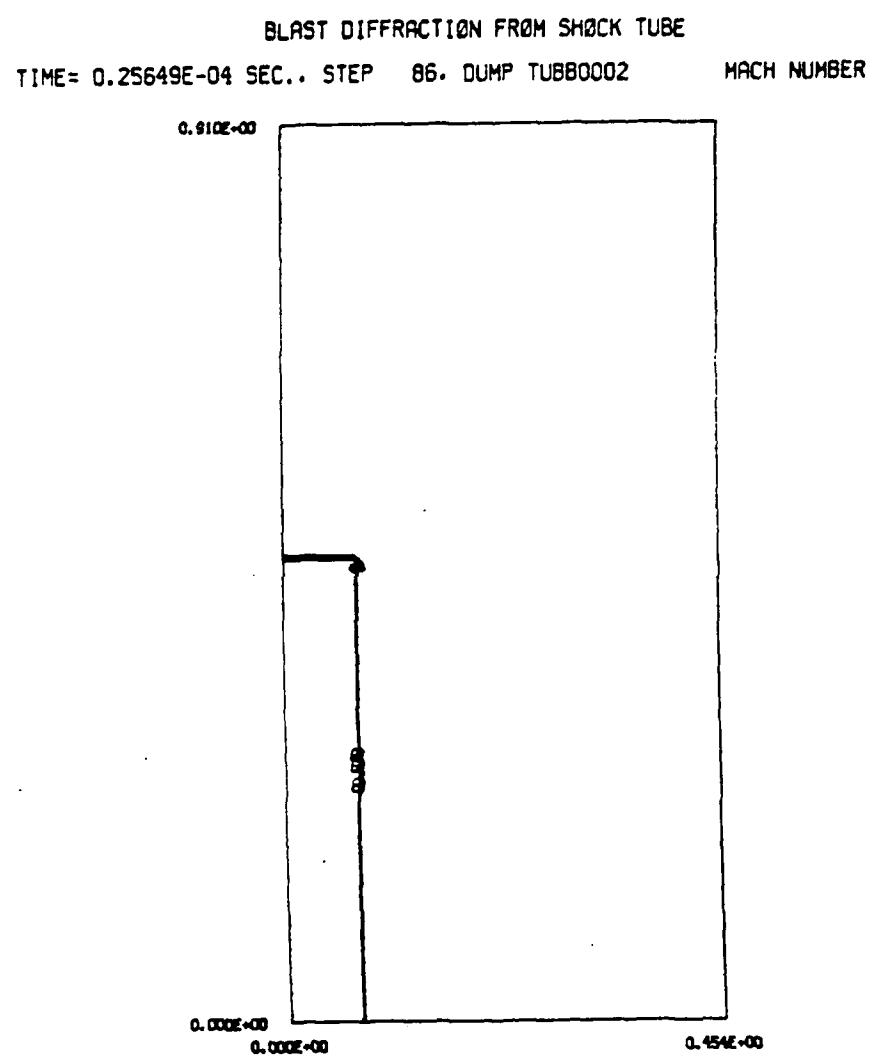
Figure 2c

BLAST DIFFRACTIØN FRØM SHØCK TUBE

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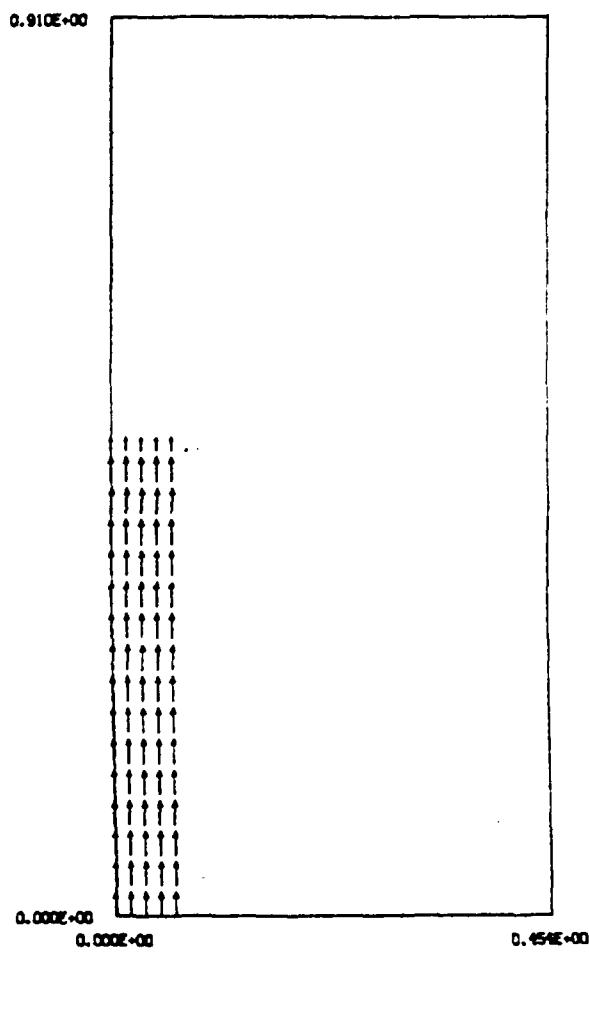

Figure 2d

BLAST DIFFRACTIØN FRØM SHØCK TUBE

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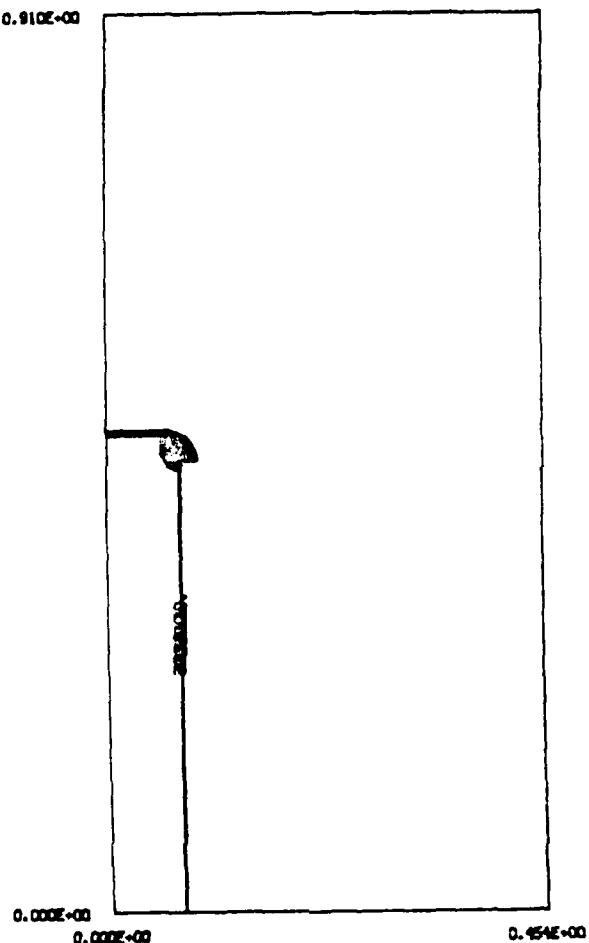
Figure 3a

BLAST DIFFRACTION FROM SHOCK TUBE

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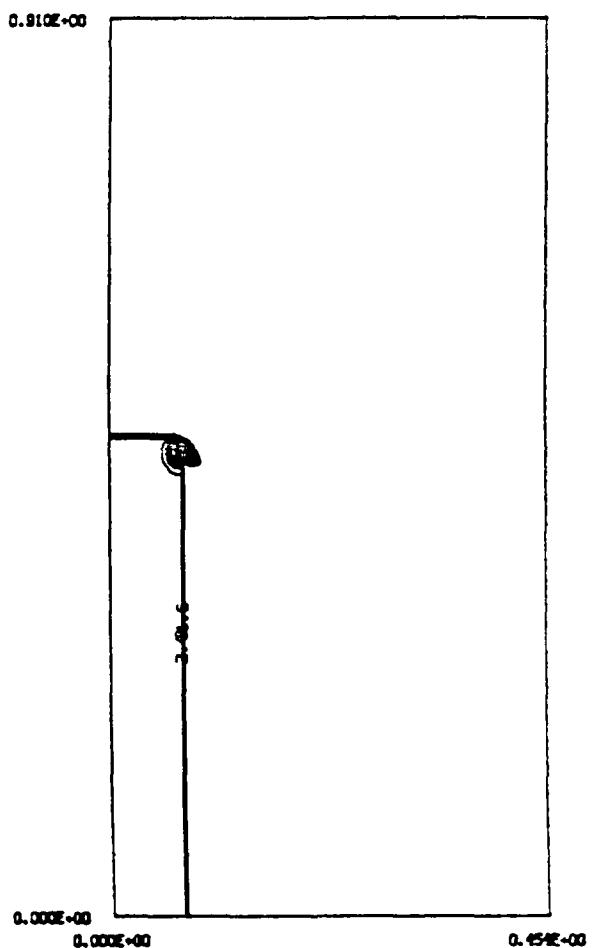
Figure 3b

BLAST DIFFRACTION FROM SHOCK TUBE

TIME= 0.50172E-04 SEC.. STEP 107. DUMP TUBB0003   MACH NUMBER

Figure 3c

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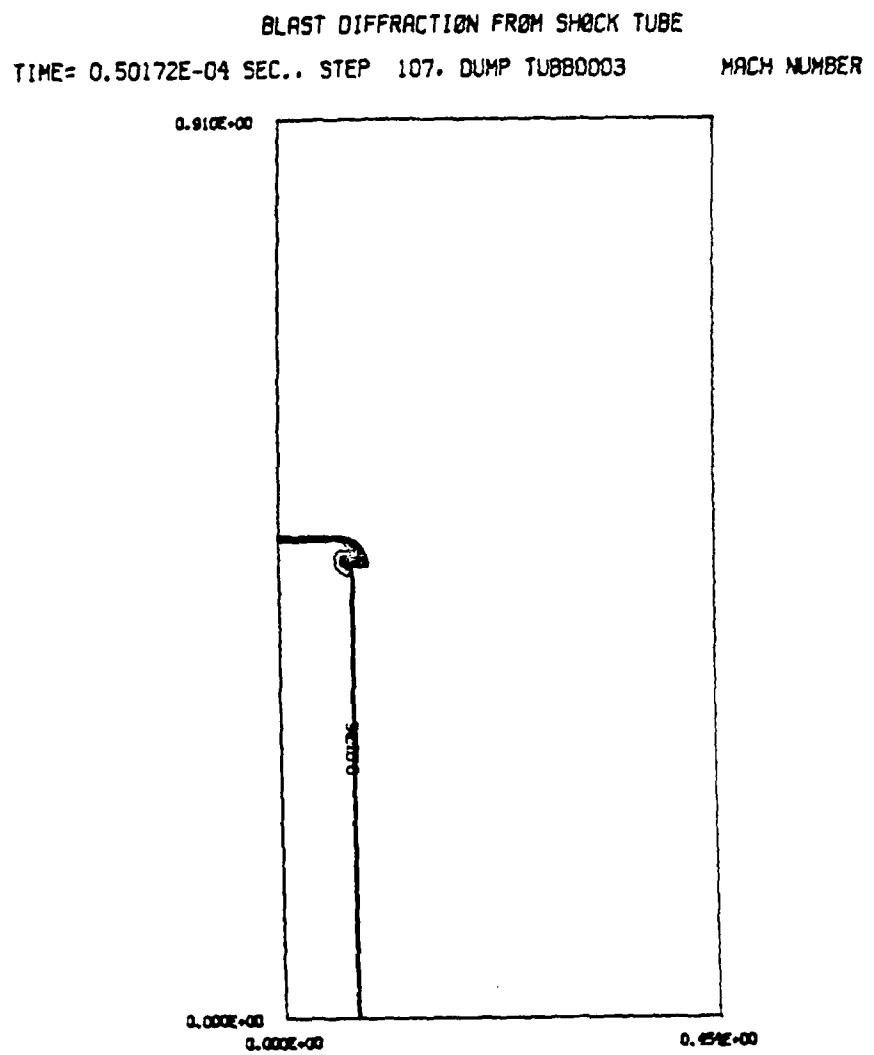
BLAST DIFFRACTION FROM SHOCK TUBE

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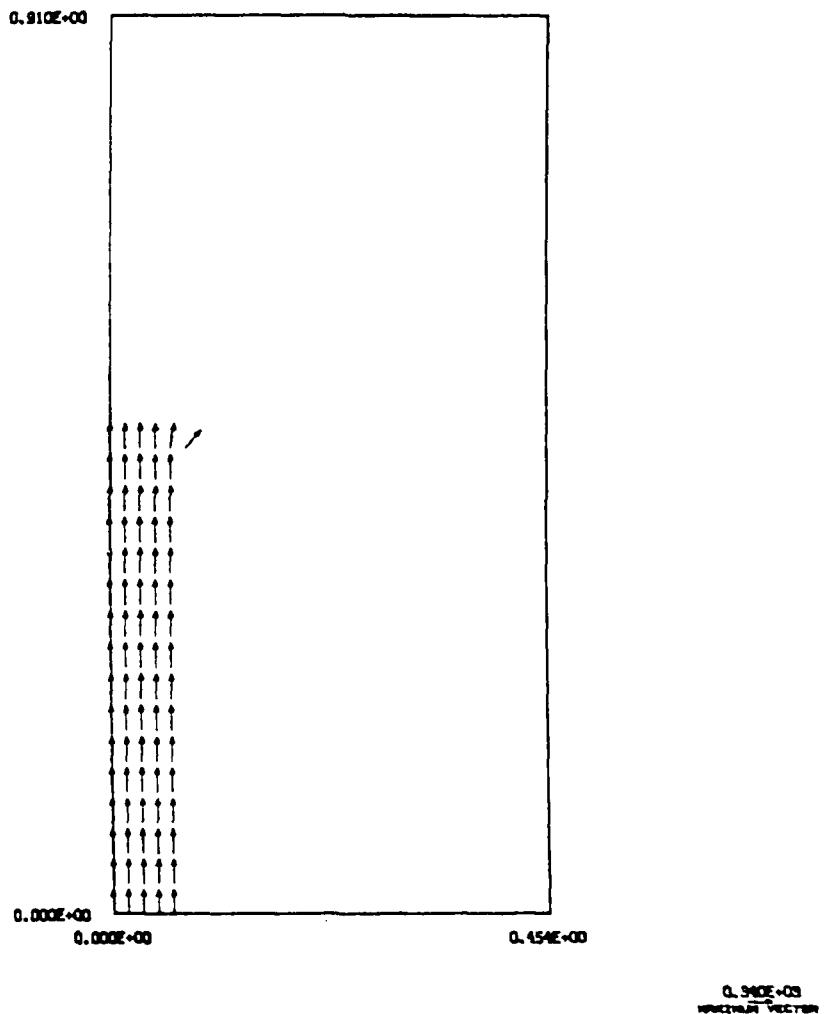
Figure 3d

BLAST DIFFRACTIØN FRØM SHØCK TUBE

TIME= 0.10014E-03 SEC., STEP 152, DUMP TUBB0004   PRESSURE,NEHTØNS/M**2

Figure 4a

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BLAST DIFFRACTIØN FRØM SHØCK TUBE
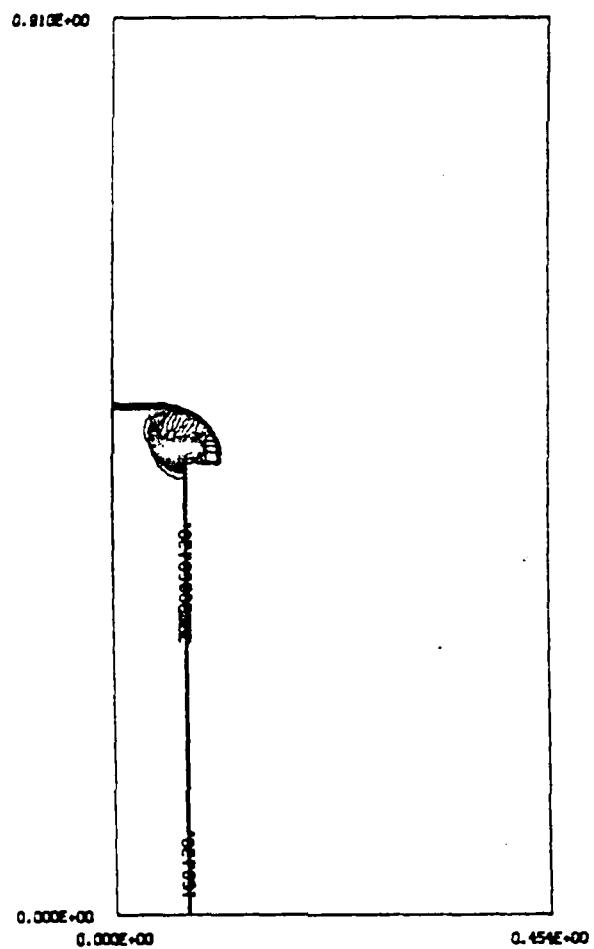
TIME= 0.10014E-03 SEC.. STEP 152, DUMP TUBB0004   DENSITY 1. KG/M3

Figure 4b

BLAST DIFFRACTIØN FRØM SHØCK TUBE

TIME= 0.10014E-03 SEC.. STEP 152. DUMP TUBB0004   MACH NUMBER
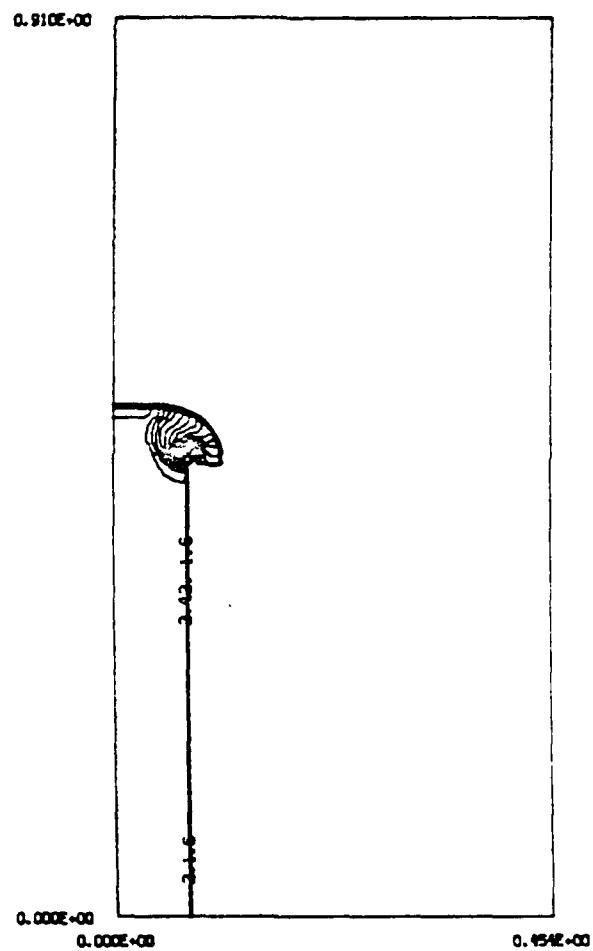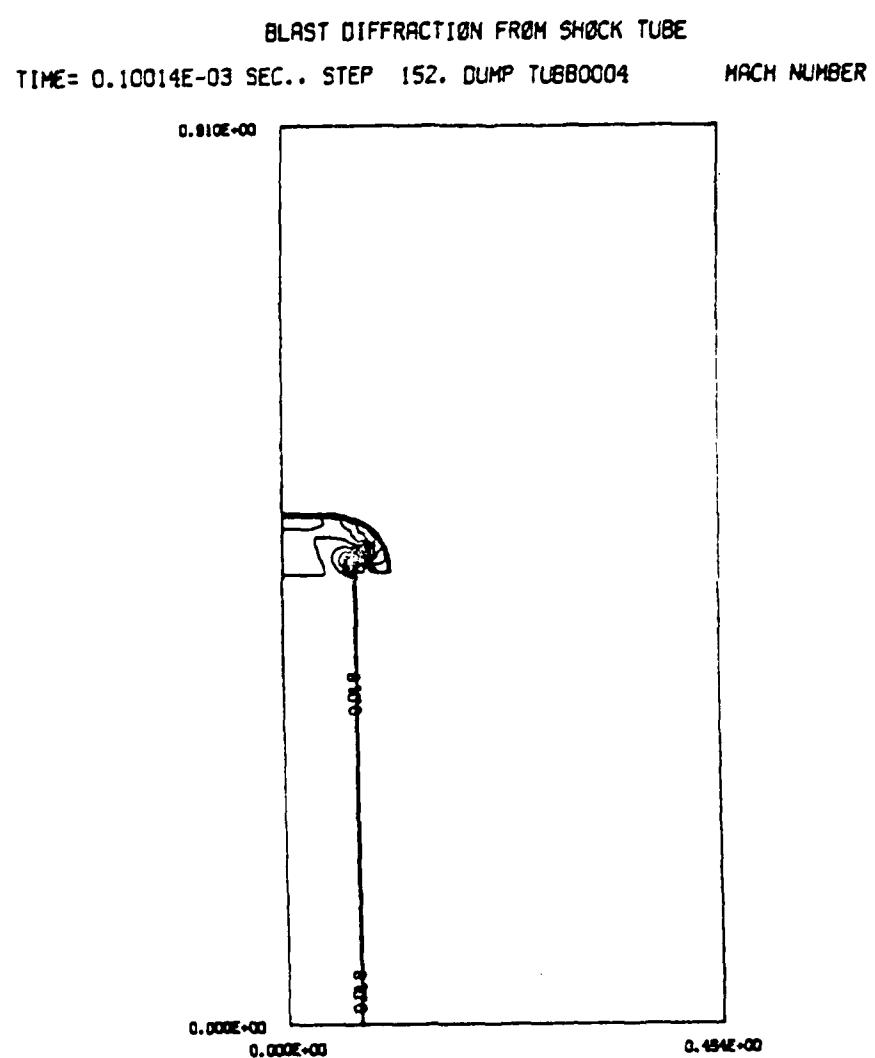
Figure 4c

BLAST DIFFRACTIØN FRØM SHØCK TUBE

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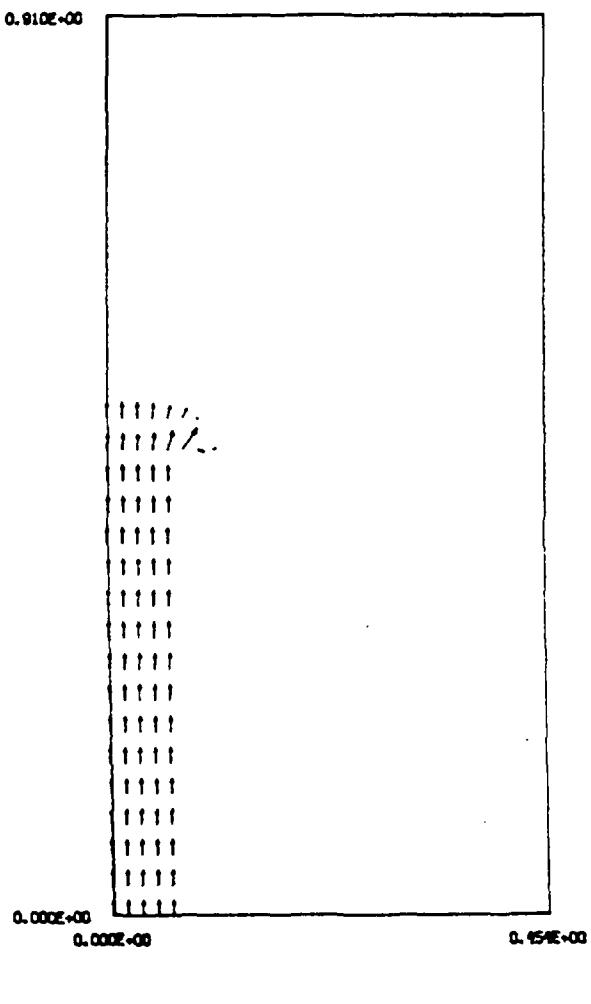
Figure 4d

BLAST DIFFRACTION FROM SHOCK TUBE

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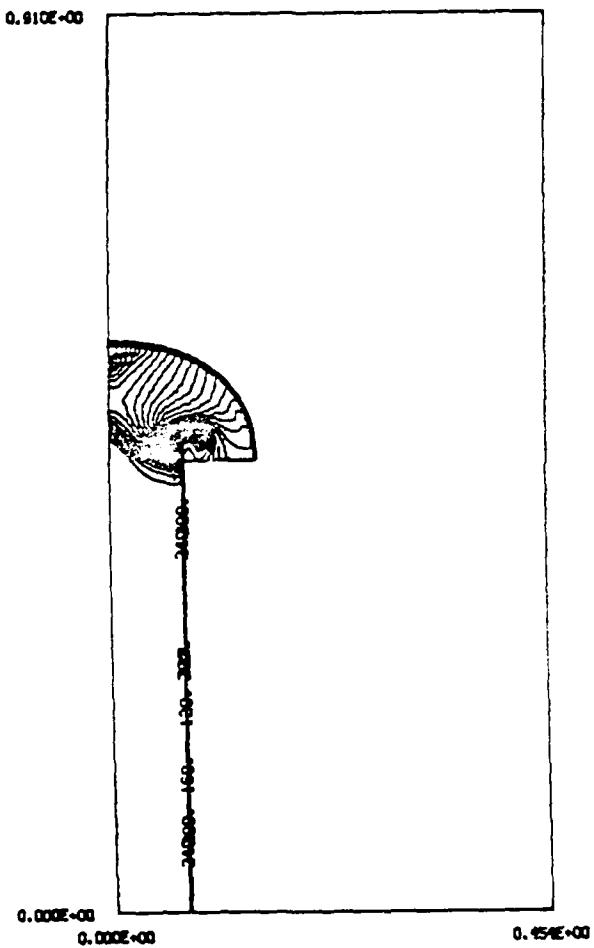
Figure 5a
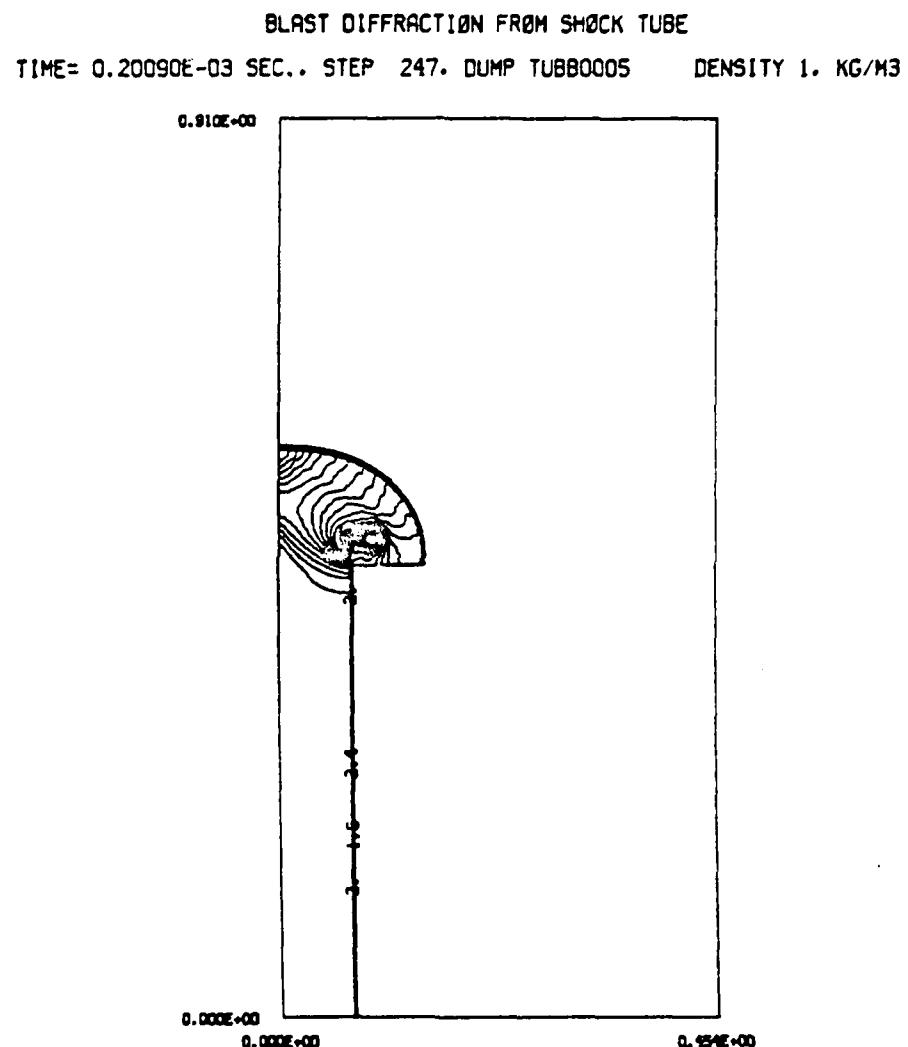
BLAST DIFFRACTION FROM SHOCK TUBE

TIME= 0.20090E-03 SEC.. STEP 247. DUMP TUBB0005   DENSITY 1. KG/M3

Figure 5b

BLAST DIFFRACTION FROM SHOCK TUBE

TIME= 0.20090E-03 SEC., STEP 247, DUMP TUBB0005   MACH NUMBER

0.910E+00

0.000E+00
0.000E+00   0.454E+00

Figure 5c

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BLAST DIFFRACTIØN FRØM SHØCK TUBE
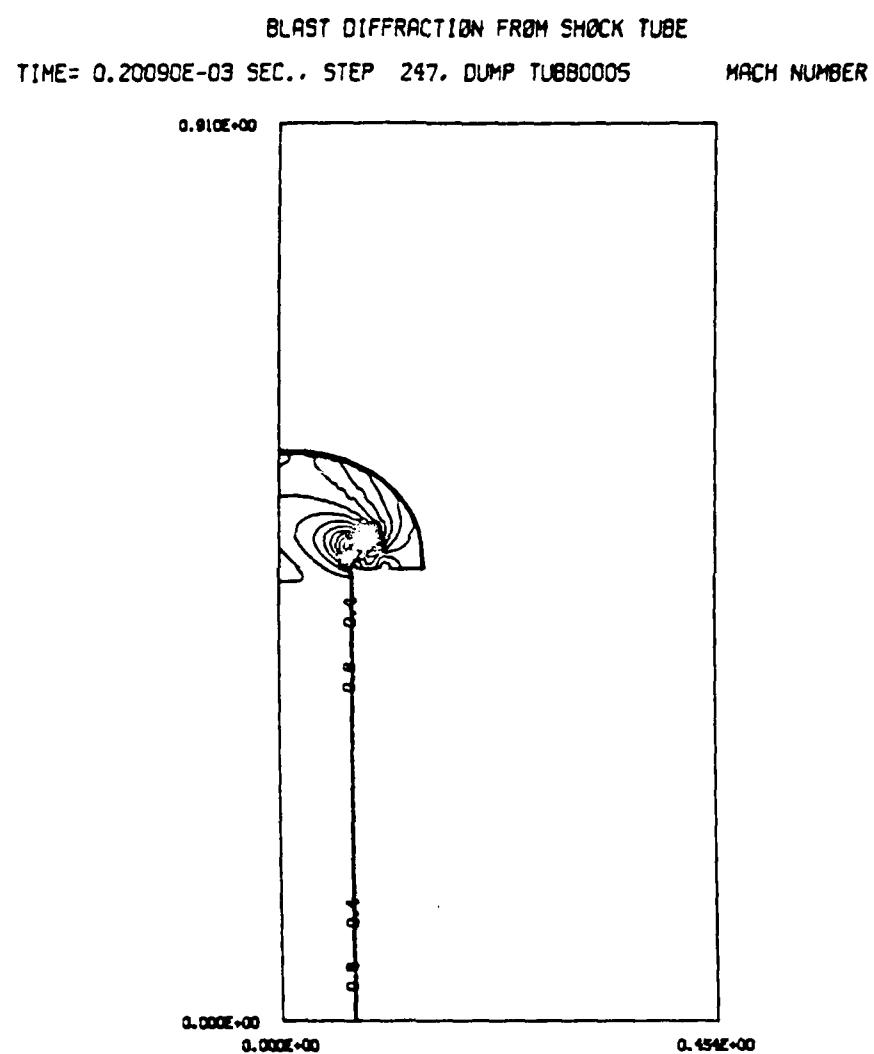
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Figure 5d

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BLAST DIFFRACTIØN FRØM SHØCK TUBE
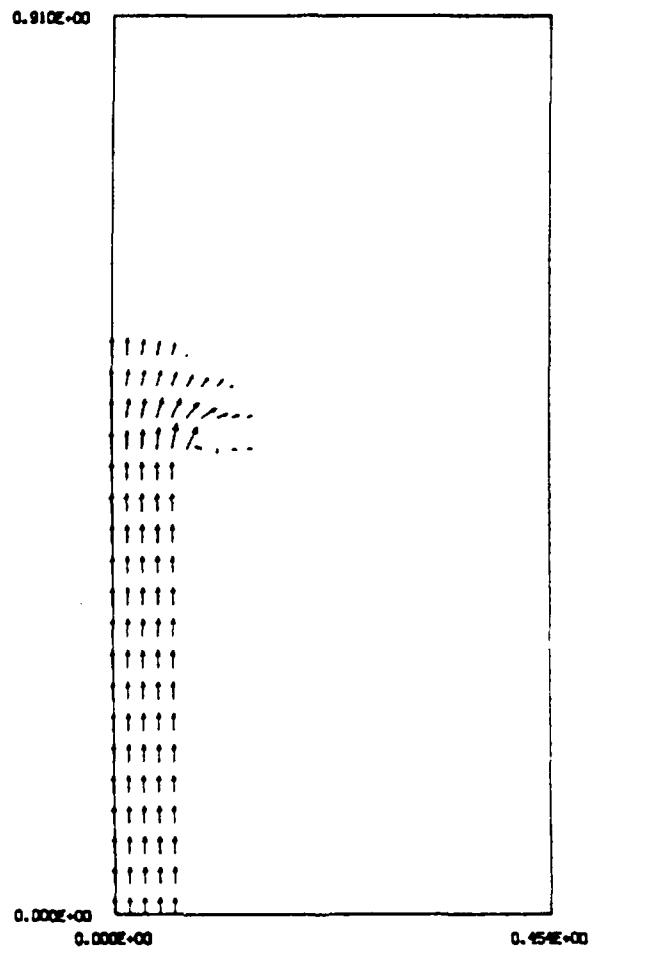
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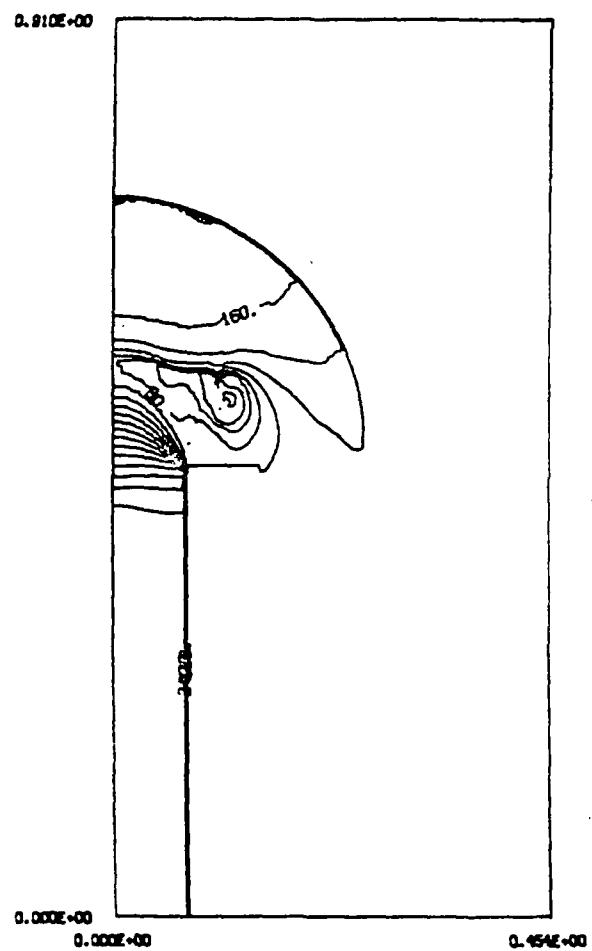
Figure 6a

BLAST DIFFRACTION FROM SHOCK TUBE

TIME= 0.50093E-03 SEC.. STEP 534. DUMP TUBB0006   DENSITY 1. KG/M3
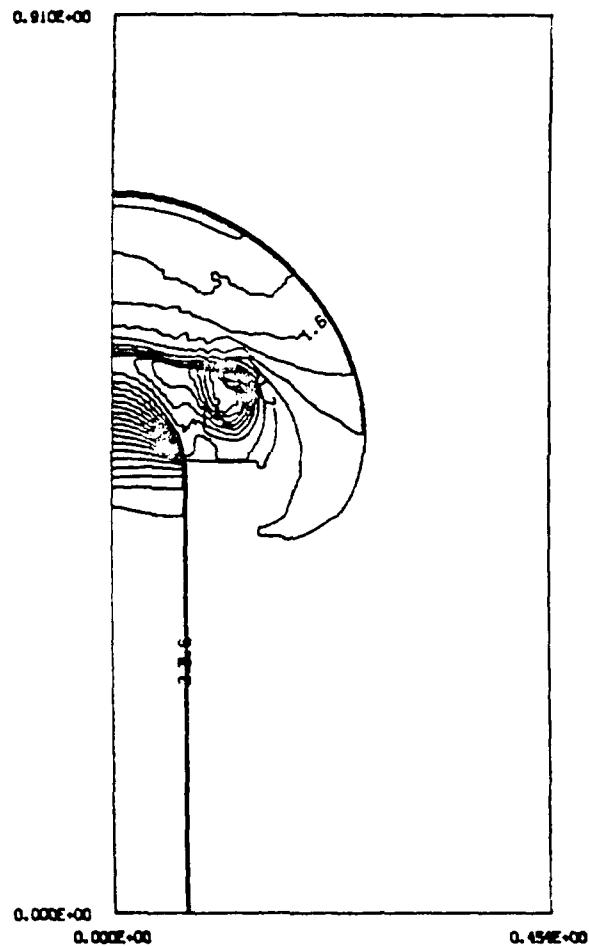
Figure 6b
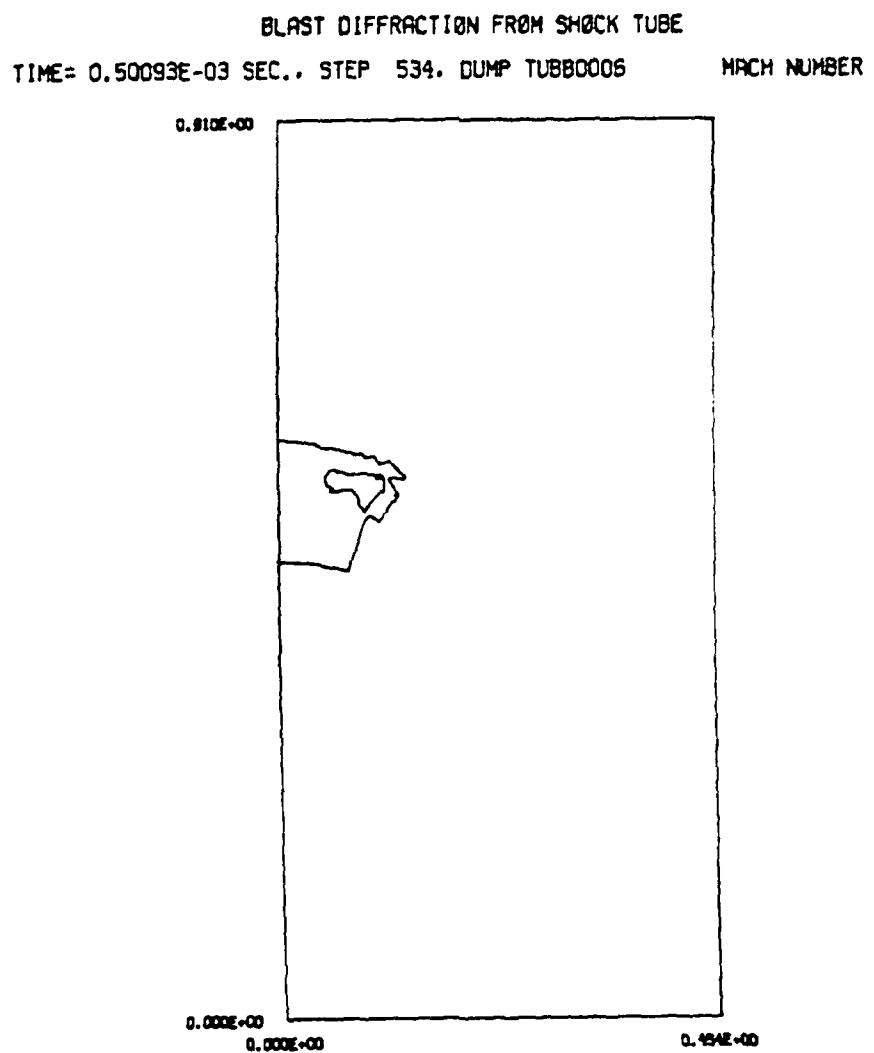
BLAST DIFFRACTION FROM SHOCK TUBE

TIME= 0.50093E-03 SEC., STEP 534. DUMP TUBB0006   MACH NUMBER

Figure 6c

33

BLAST DIFFRACTION FROM SHOCK TUBE

TIME= 0.50093E-03 SEC.. STEP 534. DUMP TUBB0006   VELOCITY. M/SEC
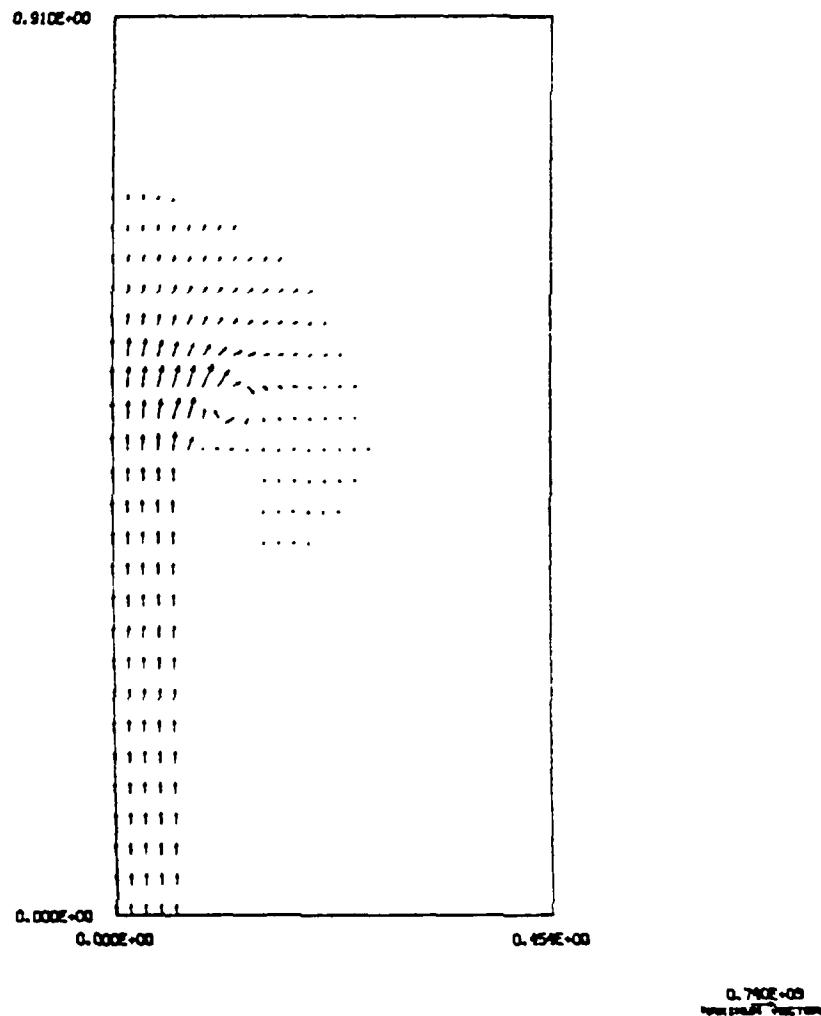
Figure 6d

BLAST DIFFRACTIØN FRØM SHØCK TUBE

TIME= 0.10007E-02 SEC., STEP 1063. DUMP TUBB0007   PRESSURE,NEWTØNS/M**2
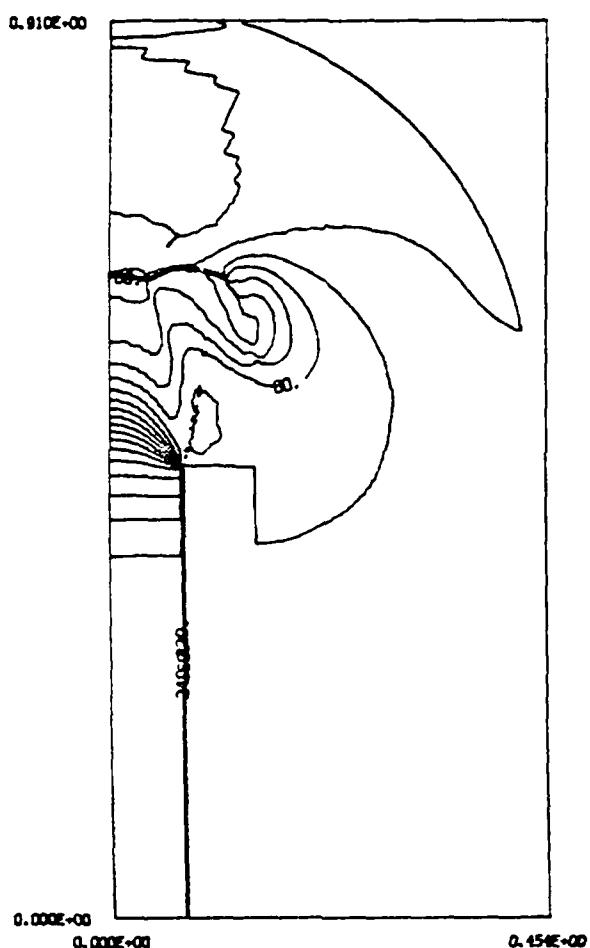
Figure 7a

BLAST DIFFRACTION FROM SHOCK TUBE

TIME= 0.10007E-02 SEC.. STEP 1063. DUMP TUBB0007   DENSITY 1. KG/M3
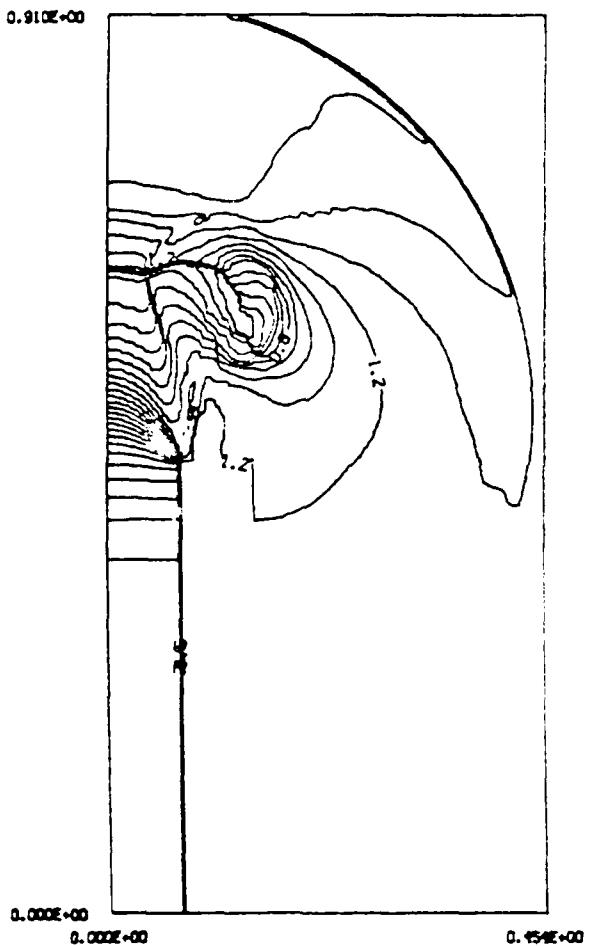
Figure 7b
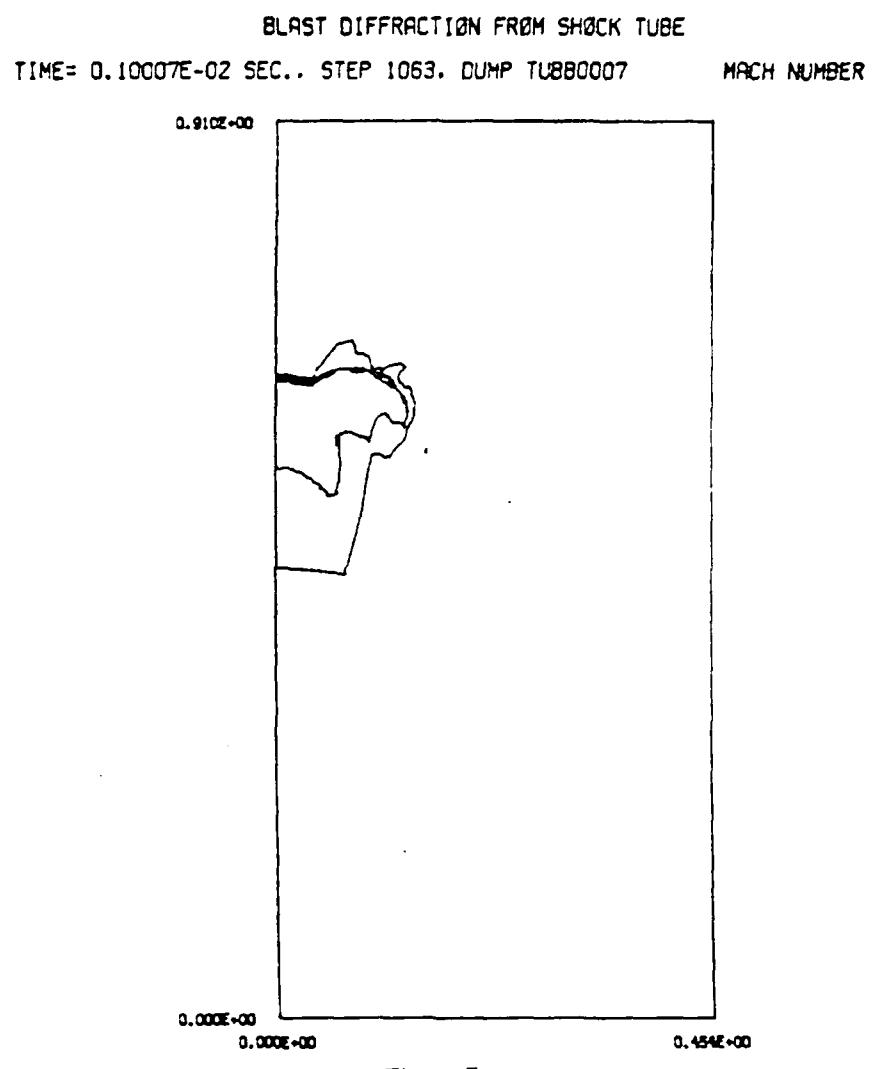
BLAST DIFFRACTIØN FRØM SHØCK TUBE

TIME= 0.10007E-02 SEC., STEP 1063, DUMP TUBB0007   MACH NUMBER

Figure 7c

37

BLAST DIFFRACTION FROM SHOCK TUBE

TIME= 0.10007E-02 SEC., STEP 1063. DUMP TUBB0007   VELOCITY. M/SEC

Figure 7d

BLAST DIFFRACTIØN FRØM SHØCK TUBE

TIME= 0.15009E-02 SEC.. STEP 1618. DUMP TUBB0008   DENSITY 1. KG/M3
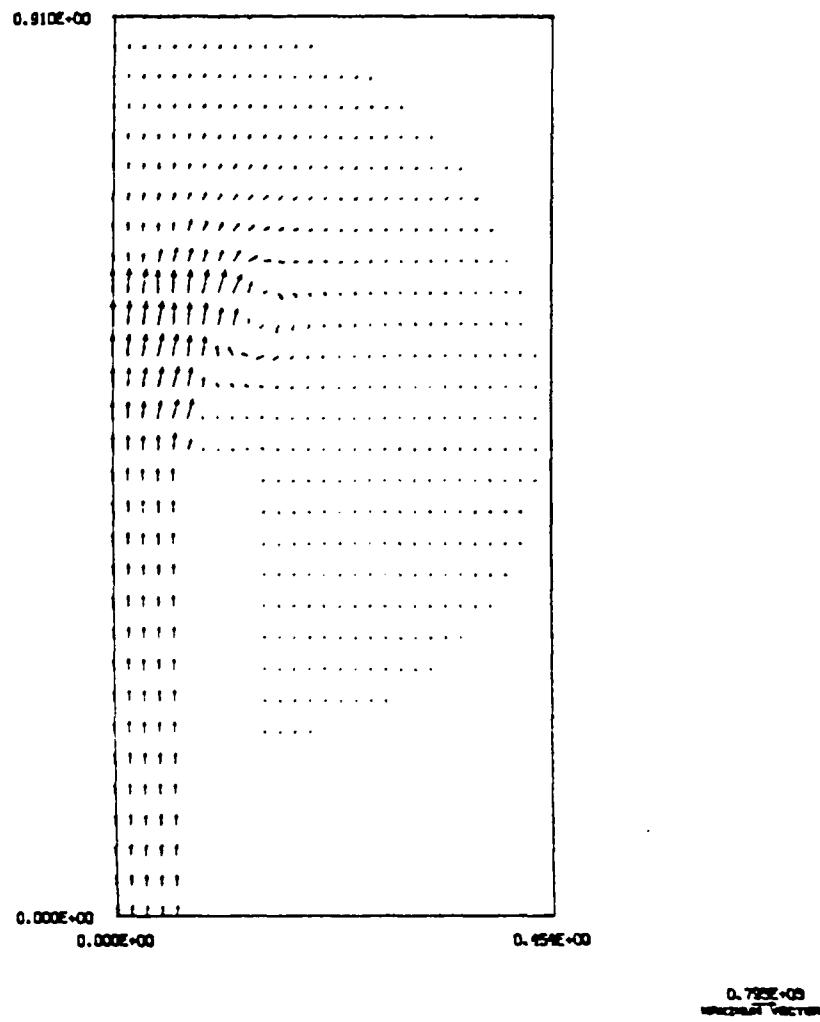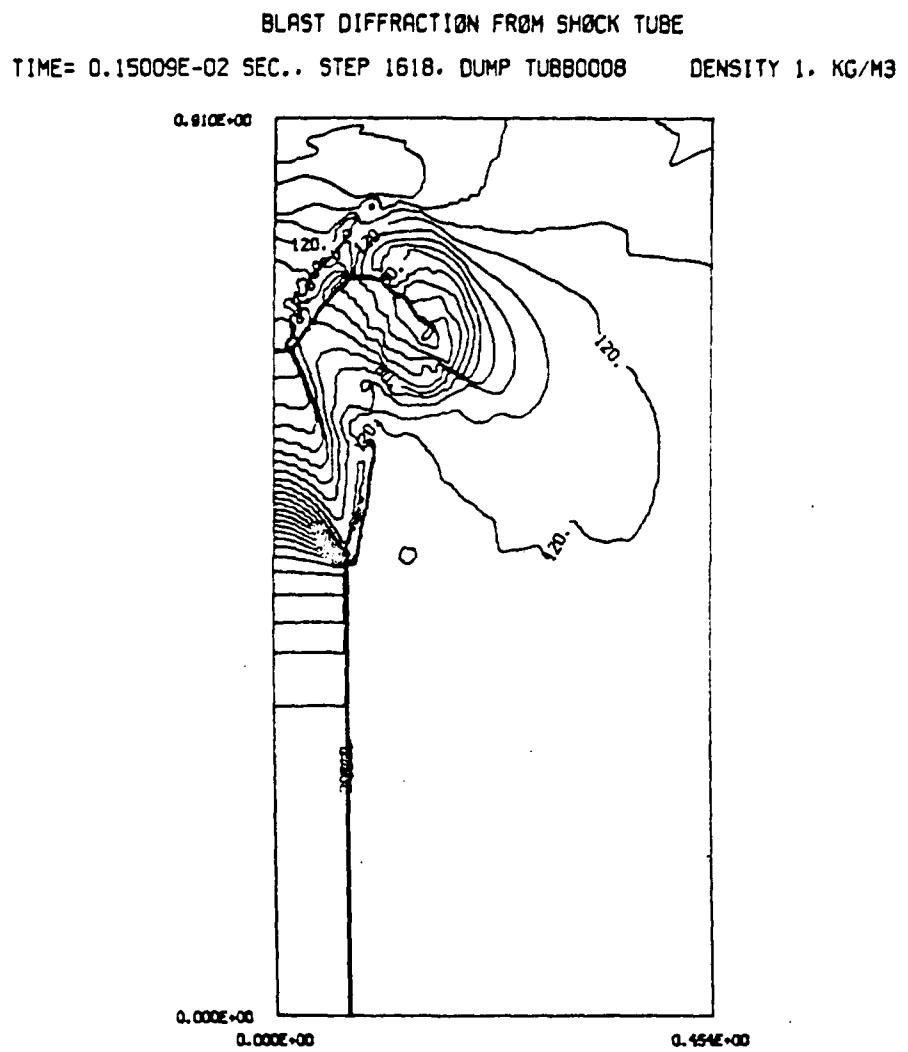
Figure 8a

BLAST DIFFRACTION FROM SHOCK TUBE

TIME= 0.15009E-02 SEC.. STEP 1618. DUMP TUB80008   PRESSURE.NEWTONS/M**2
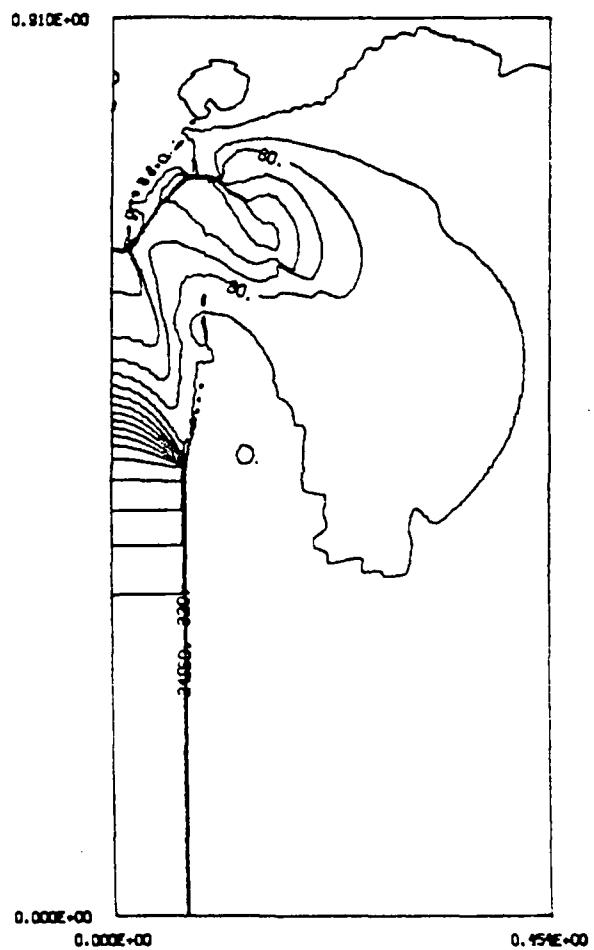
0.910E+00

80.

80.

O.

0.000E+00

0.000E+00   0.454E+00

Figure 8b

40

BLAST DIFFRACTIØN FRØM SHØCK TUBE

TIME= 0.15009E-02 SEC.. STEP 1618. DUMP TUB80008   MACH NUMBER

Figure 8c

41
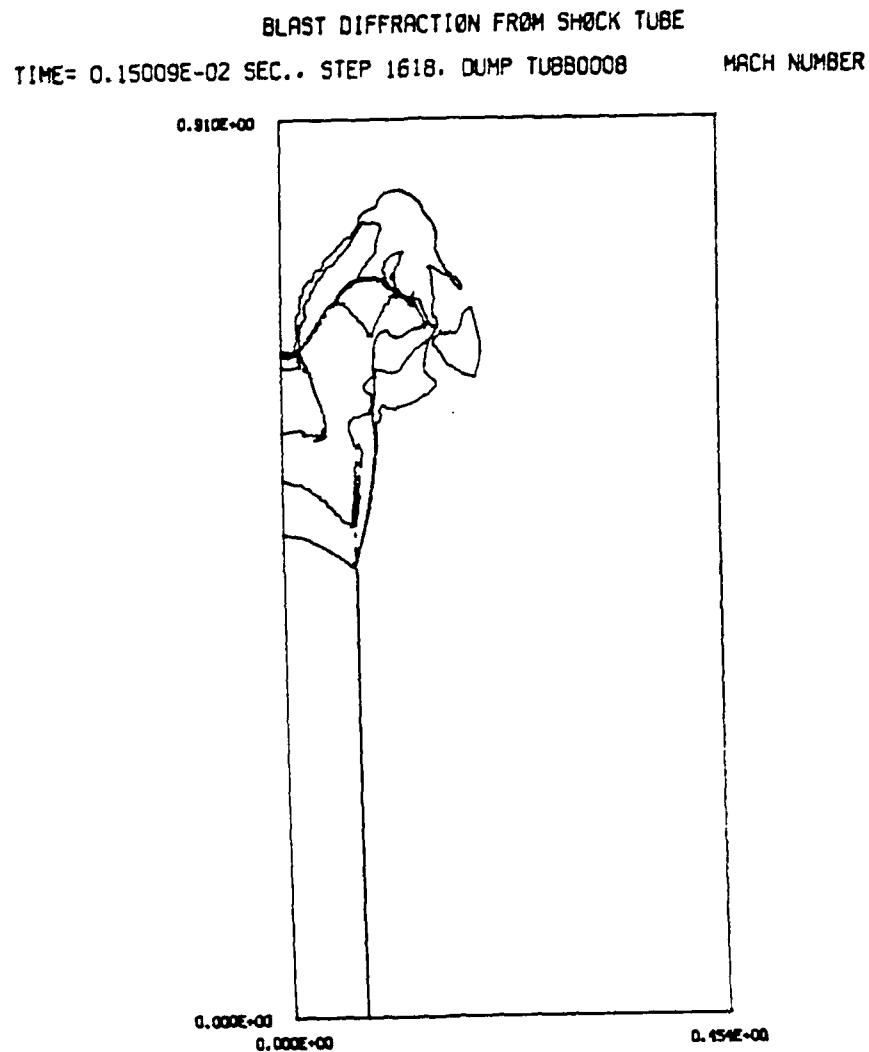
BLAST DIFFRACTION FROM SHOCK TUBE

TIME= 0.15009E-02 SEC., STEP 1618, DUMP TUBB0008   VELOCITY, M/SEC

Figure 8d

STATIØN 1. XS.YS= 0.115E-02 0.684E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TU360008

Figure 9a

43

STATIØN 1. XS.YS= 0.115E-02 0.684E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TLG80008

Figure 9b

44

STATIØN 1. XS.YS= 0.115E-02 0.684E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE
7 DUMPS. LAST DUMP IS TU880008

Figure 9c

45

STATIØN 2. XS,YS= 0.114E+00 0.653E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TUBBODOB

Figure 10a

46

STATIØN 2. XS.YS= 0.114E+00 0.653E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TUBBOO08

Figure 10b

47

STATION 2. XS,YS= 0.114E+00 0.653E+00 M

BLAST DIFFRACTION FROM SHOCK TUBE

7 DUMPS. LAST DUMP IS TUBB0008

Figure 10c

48

STATIØN 3, XS.YS= 0.197E+00 0.570E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TU88000B

Figure 11a

49

STATIØN 3. XS,YS= 0.197E+00 0.570E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TUBBOCOS

Figure 11b

50

STATIØN 3. XS.YS= 0.197E+00 0.570E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LALT DUMP IS TU33OOO9

Figure 11c

51

STATIØN 4. XS.YS= 0.228E+00 0.456E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TUB80008

Figure 12a

52

STATIØN 4. XS.YS= 0.228E+00 0.456E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TU880008

Figure 12b

53

STATIØN 4, XS,YS= 0.228E+00 0.456E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TUBB0008

Figure 12c

54

STATIØN 5. XS.YS= 0.197E+00 0.342E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TL=5000CS

Figure 13a

STATIØN 5. XS.YS= 0.197E+00 0.342E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TUB8OOO8

Figure 13b

STATION 5, XS,YS= 0.197E+00 0.342E+00 M

BLAST DIFFRACTION FROM SHOCK TUBE

7 DUMPS, LAST DUMP IS TL830009

Figure 13c

57

STATION 6. XS,YS= 0.175E+00 0.309E+00 M

BLAST DIFFRACTION FROM SHOCK TUBE

7 DUMPS. LAST DUMP IS TUBSCOO8

Figure 14a

58

STATIØN 6. XS.YS= 0.175E+00 0.309E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TL880008

Figure 14b

STATIØN 6. XS.YS= 0.175E+00 0.309E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TU88000B

Figure 14c

60

STATIØN 7. XS,YS= 0.152E+00 0.286E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TUBBOOO8

Figure 15a

61

STATIØN 7. XS.YS= 0.152E+00 0.286E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE
7 DUMPS. LAST DUMP IS TUB8000B

Figure 15b

62

STATIØN 7. XS.YS= 0.152E+00 0.286E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TUBB0008

Figure 15c

63

STATIØN 10. XS,YS= 0.115E-02 0.667E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TUB30008

Figure 16a

64

STATIØN 10. XS.YS= 0.115E-02 0.667E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TUBBODOB

Figure 16b

65

STATIØN 10. XS.YS= 0.115E-02 0.667E+00 M

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TUB80008

Figure 16c

66

STATIØN 1, XS,YS= 0.115E-02 0.684E+00 M.

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS, LAST DUMP IS TUBB0008

Figure 17

67

STATIØN 2. XS,YS= 0.114E+00 0.653E+00 M.

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS, LAST DUMP IS TUBBOOO8

Figure 18

68

STATION 3, XS,YS= 0.197E+00 0.570E+00 M.

PEAK VALUE= 0.49212E+05

BLAST DIFFRACTION FROM SHOCK TUBE

7 DUMPS, LAST DUMP IS TUBB0008

Figure 19

69

STATION 4, XS,YS= 0.228E+00 0.456E+00 M.

BLAST DIFFRACTION FROM SHOCK TUBE

7 DUMPS, LAST DUMP I3 TUBE0008

Figure 20

70

STATION 5. XS,YS= 0.197E+00 0.342E+00 M.

PEAK VALUE= 0.6853OE+04

BLAST DIFFRACTION FROM SHOCK TUBE

7 DUMPS, LAST DUMP IS TUBBOIOO8

Figure 21

71

STATIØN 6. XS,YS= 0.175E+00 0.309E+00 M.

PEAK VALUE= 0.61133E+04

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS, LAST DUMP IS TUBEC0008

Figure 22

72

BLAST DIFFRACTION FROM SHOCK TUBE
7 DUMPS. LAST DUMP IS TUB80008

Figure 23

STATIØN 8. XS.YS= 0.115E-02 0.662E+00 M.

PEAK VALUE= 0.11217E+06

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS, LAST DUMP IS TUBE0008

Figure 24

74

STATION 9. XS.YS= 0.115E-02 0.665E+00 M.

PEAK VALUE= 0.10680E+06

BLAST DIFFRACTION FROM SHOCK TUBE

7 DUMPS, LAST DUMP IS TUBEC008

Figure 25

75

STATIØN 10. XS.YS= 0.115E-02 0.667E+00 M.

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TUEB0008

Figure 26
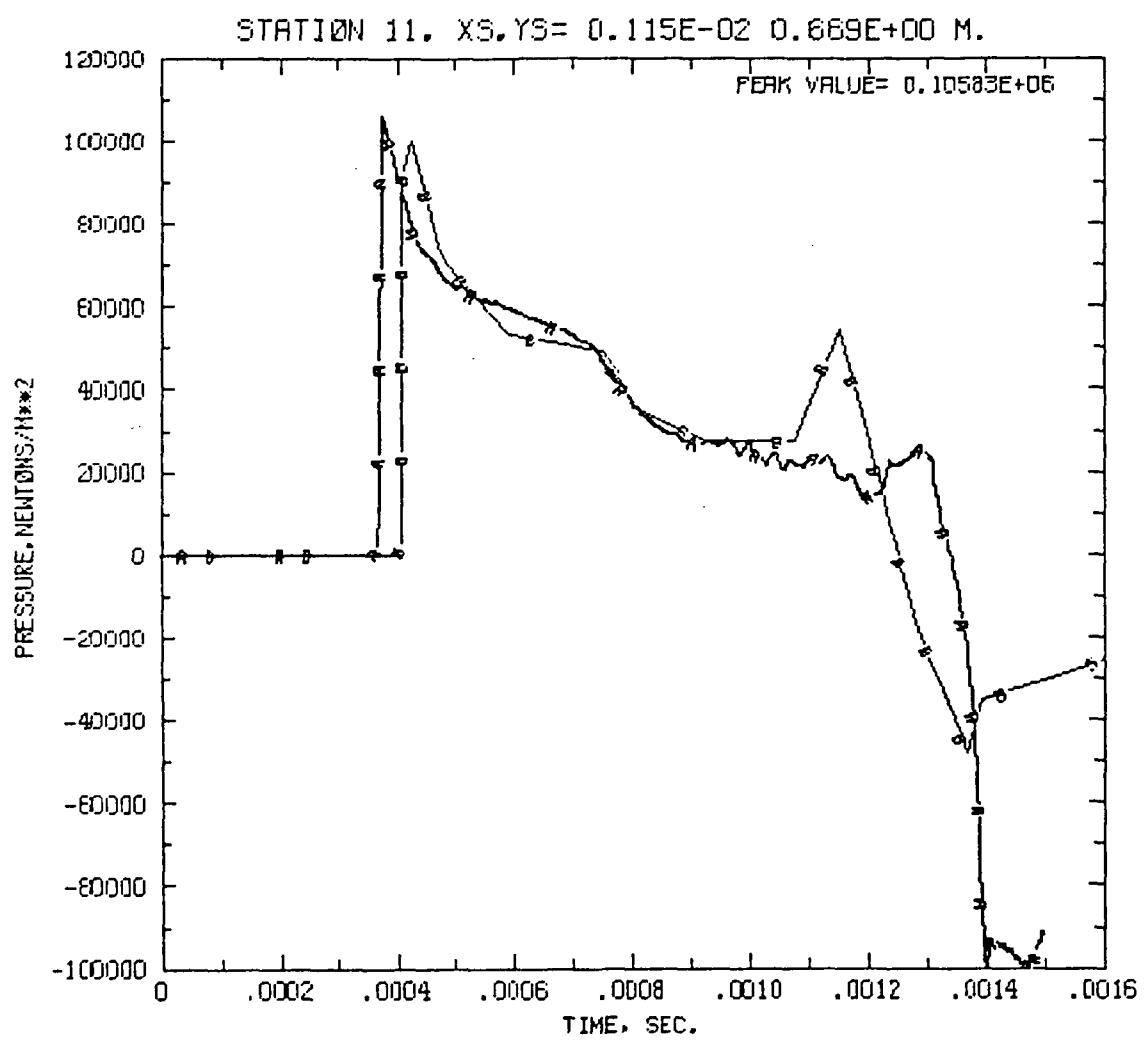
76

STATIØN 11. XS.YS= 0.115E-02 0.669E+00 M.

PEAK VALUE= 0.10583E+06

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS, LAST DUMP I3 TUBB0008

Figure 27

77

STATIØN 12. XS.YS= 0.115E-02 0.671E+00 M.

PEAK VALUE= 0.10452E+06

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP IS TUBE0008

Figure 28

78

STATIØN 13. XS.YS= 0.115E-02 0.674E+00 M.

BLAST DIFFRACTIØN FRØM SHØCK TUBE

7 DUMPS. LAST DUMP 13 TUBE0006

Figure 29

79

STATIØN 14. XS.YS= 0.115E-02 0.676E+00 M.

BLAST DIFFRACTIØN FRØM SHØCK TUBE
7 DUMPS, LAST DUMP IS TUBBOOO8
Figure 30

80

STATION 15. XS,YS= 0.115E-02 0.676E+00 M.

ELAST DIFFRACTION FROM SHOCK TUBE

7 DUMPS, LAST DUMP IS TUBB0008

Figure 31

81

STATION 16, XS,YS= 0.115E-02 0.661E+00 M.

PEAK VALUE= 0.96458E+05

ELAST DIFFRACTION FROM SHOCK TUBE

7 DUMPS, LAST DUMP IS TUBB0008

Figure 32

82
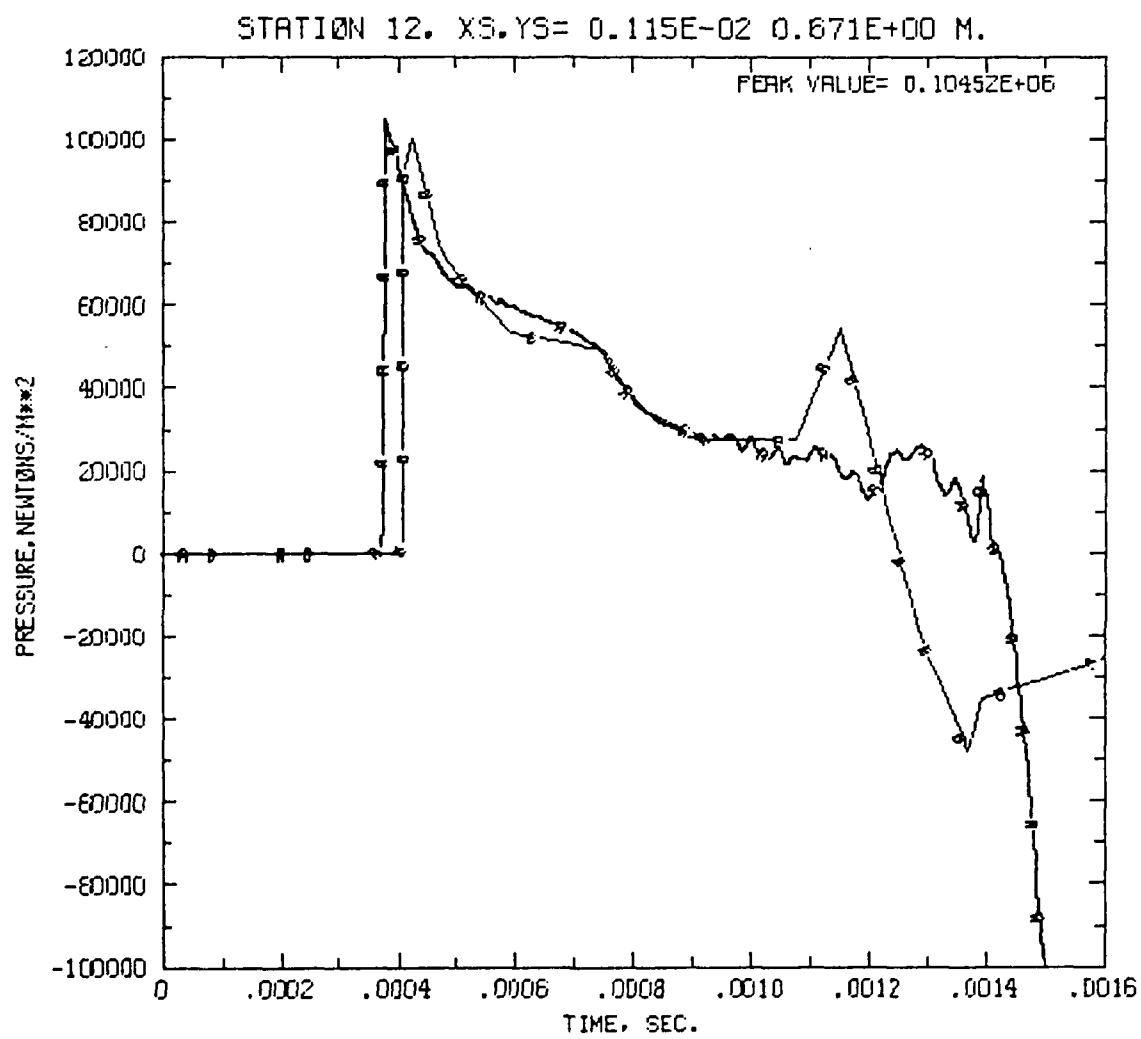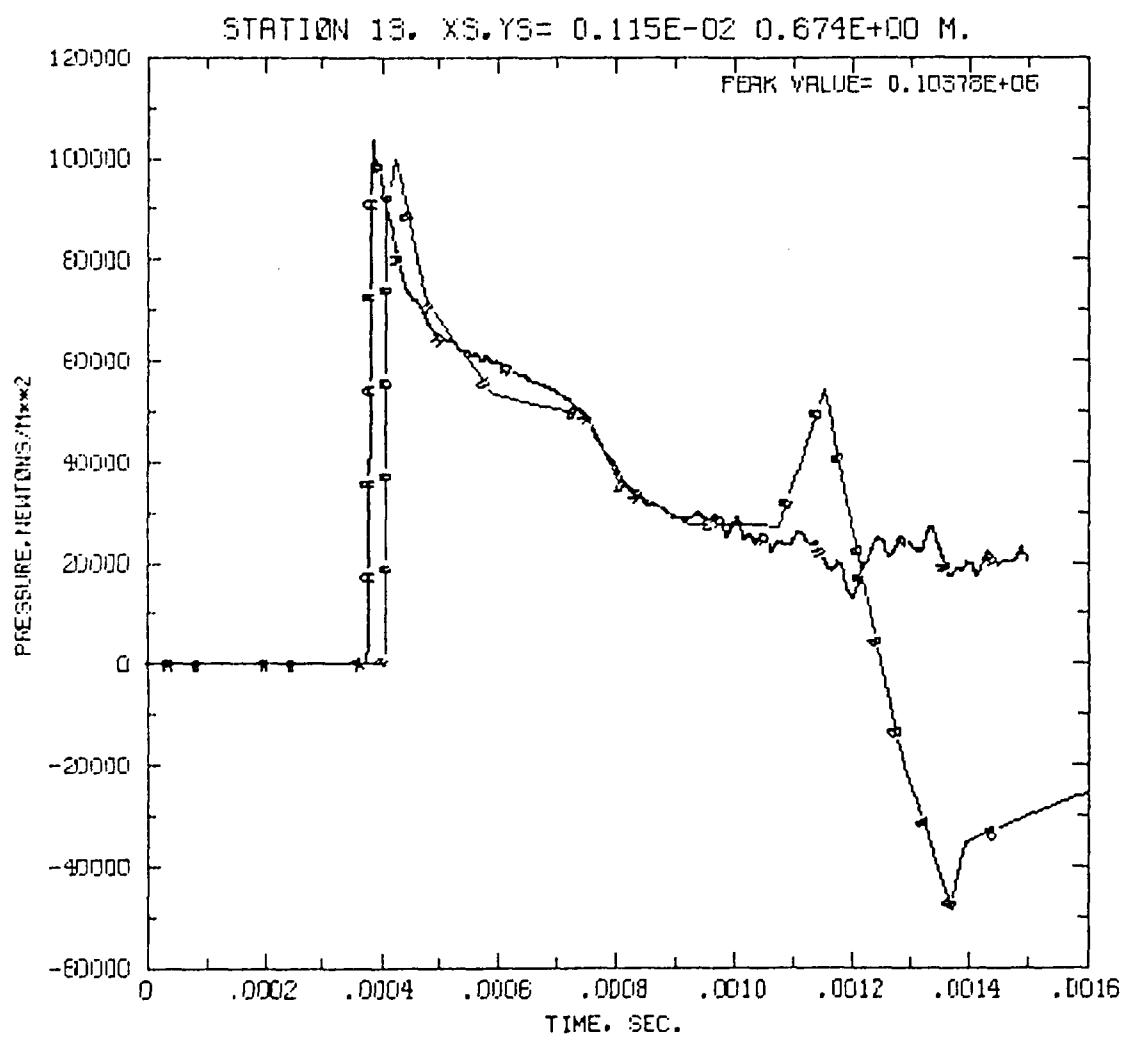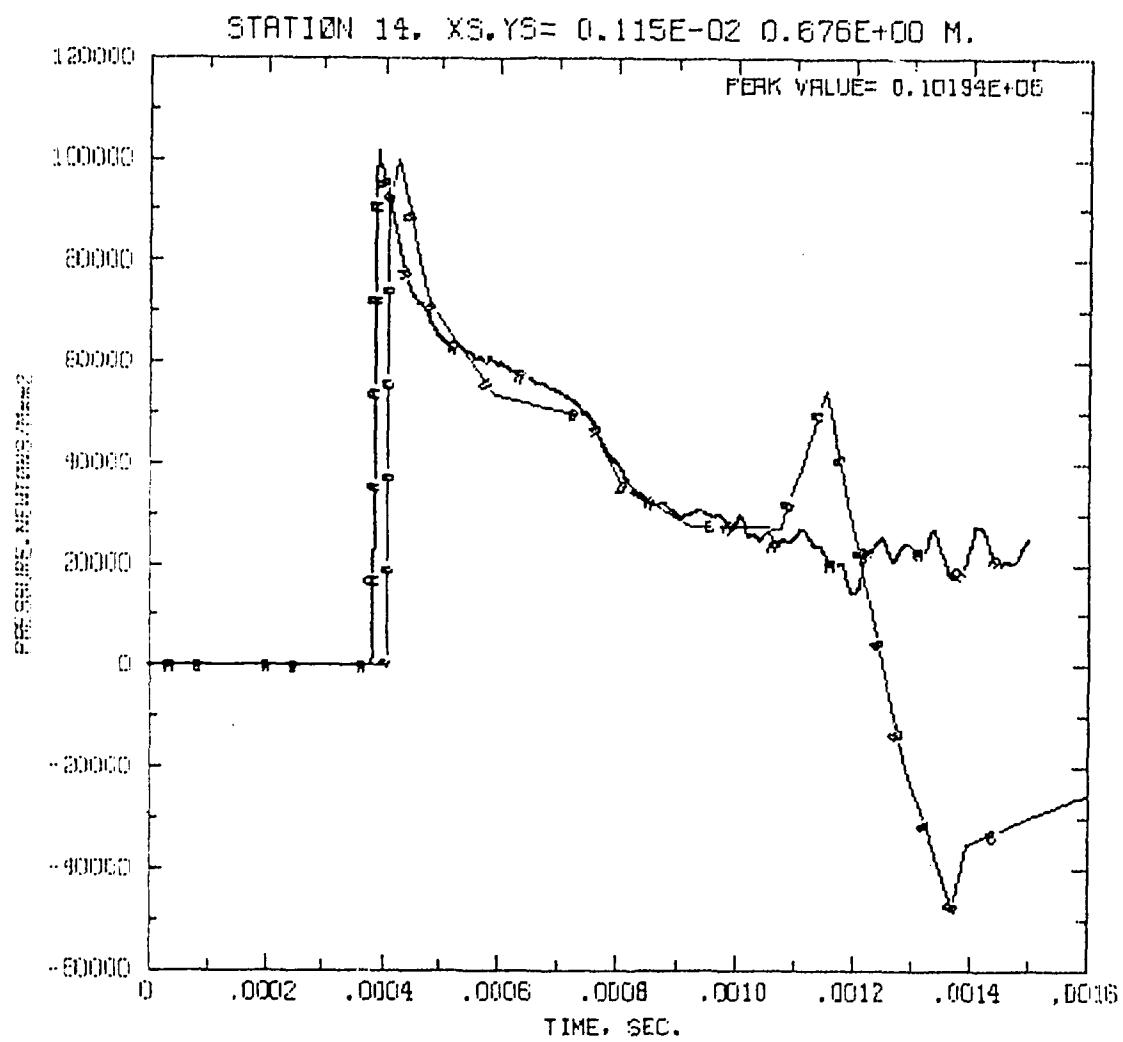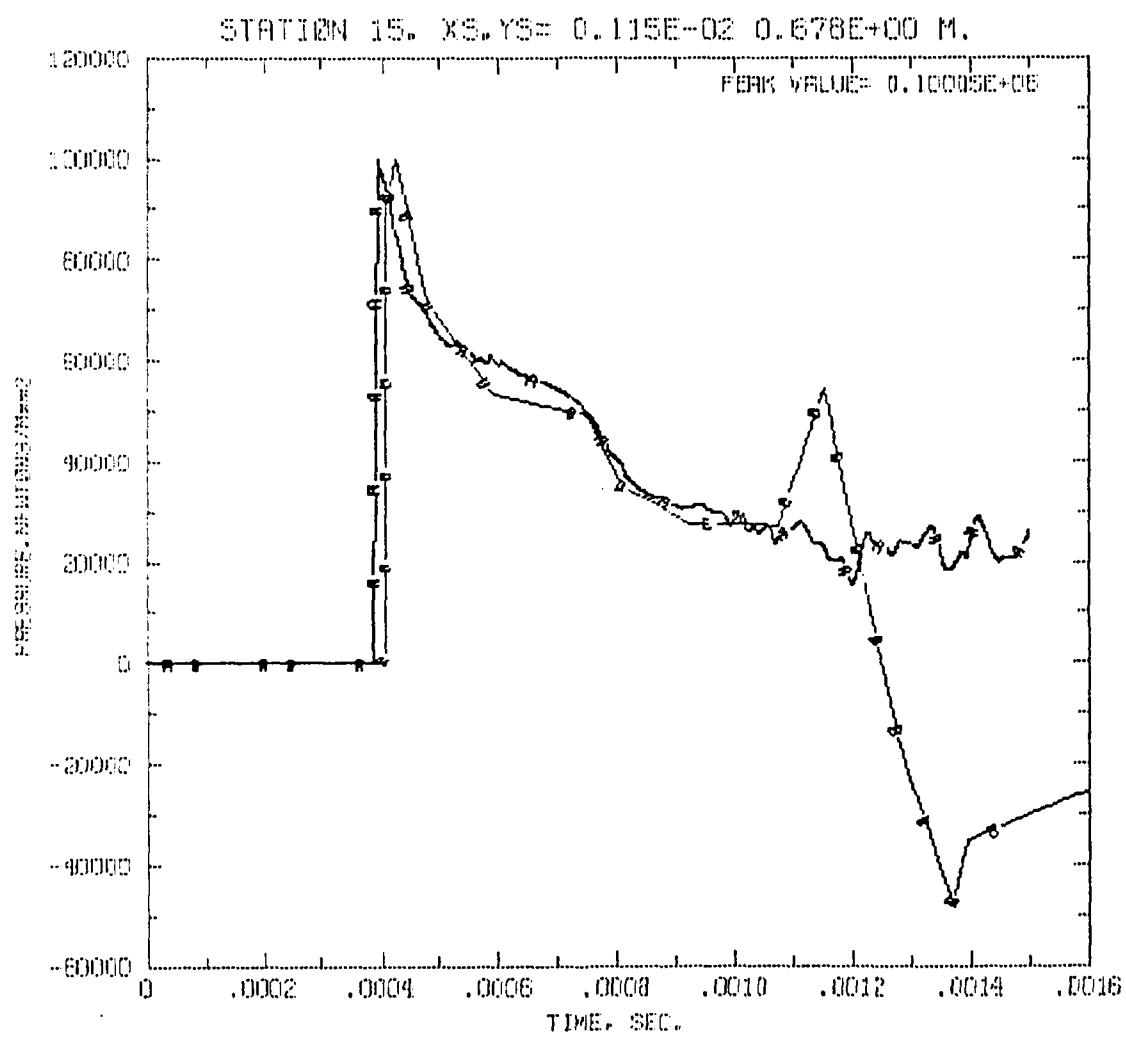
BLAST DIFFRACTION FROM SHOCK TUBE

7 DUMPS, LAST DUMP 13 TUBB0008

Figure 33
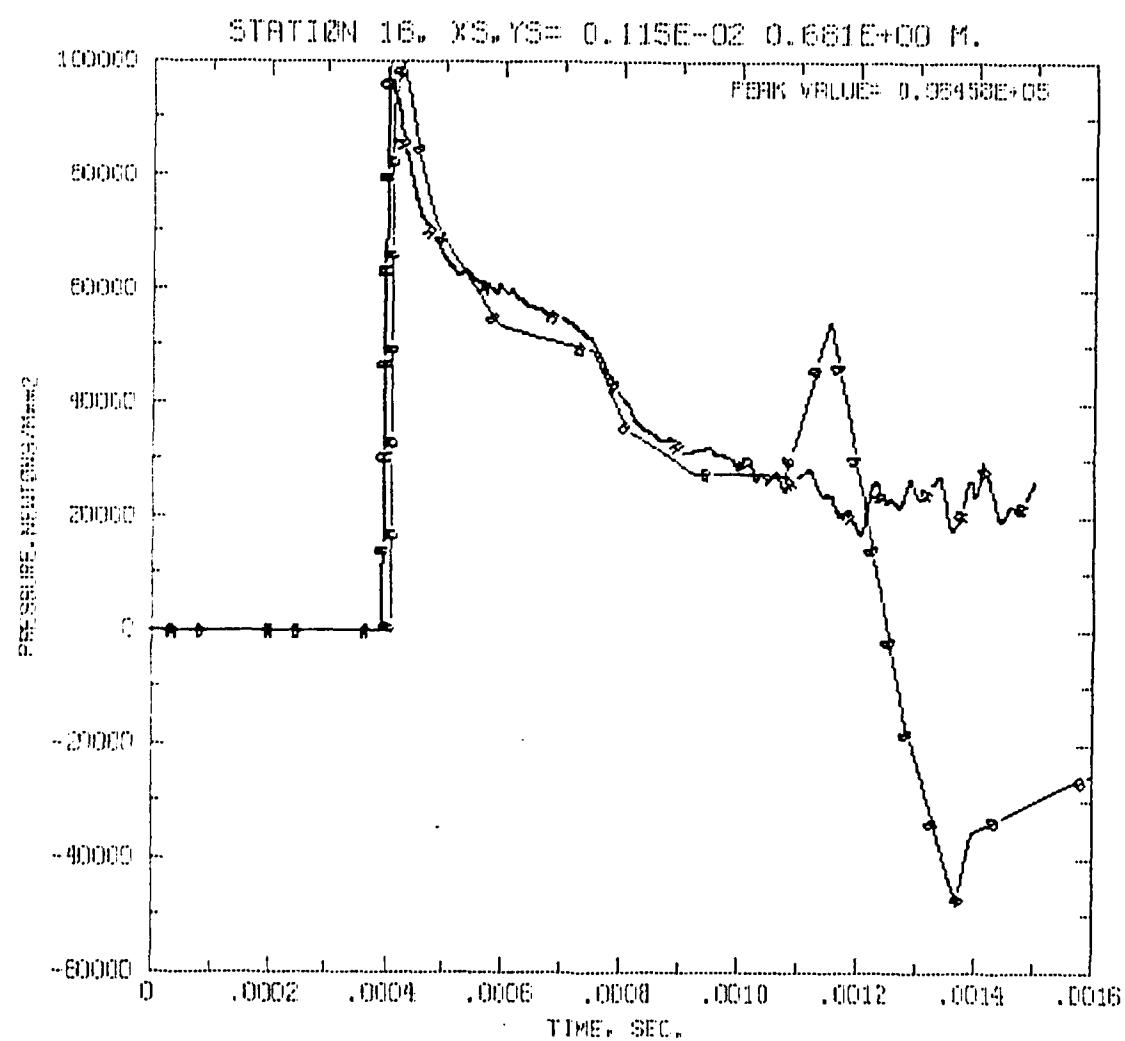
83

105 MM HØWITZER MUZZLE FLØW

TIME= 0.25352E-04 SEC., STEP   89, DUMP HØWZ0001   PRESSURE.NEWTØNS/M==2

Figure 34a

105 MM HØWITZER MUZZLE FLØW

TIME= 0.25352E-04 SEC., STEP   89. DUMP HØWZ0001   DENSITY 1. KG/M3

Figure 34b

85

105 MM HØWITZER MUZZLE FLØW

TIME= 0.25352E-04 SEC.. STEP 89. DUMP HØWZ0001 MACH NUMBER

0.827E+00

H
0.

L

L
10.0.

H   H   H
0. 0. 0.

L
0.

0.000E+00

0.000E+00   0.312E+00

CØNTØUR FRØM 0.00000   TØ 9.0000   CØNTØUR INTERVAL ØF 0.50000   PT(3.3)= 1.1346

Figure 34c

86
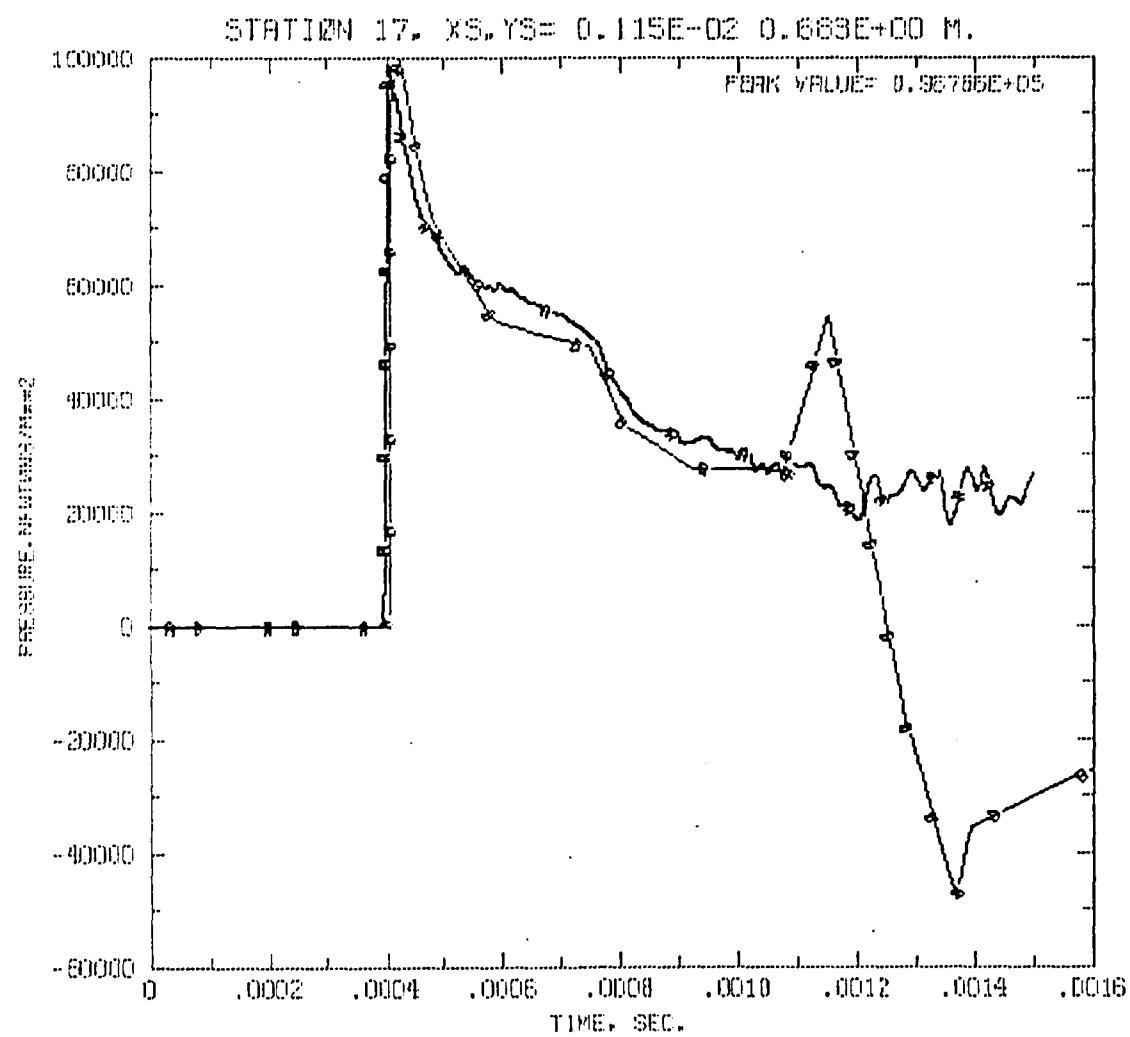
105 MM HOWITZER MUZZLE FLOW

TIME= 0.25352E-04 SEC., STEP   69. DUMP HOWZ0001   VELOCITY, M/SEC
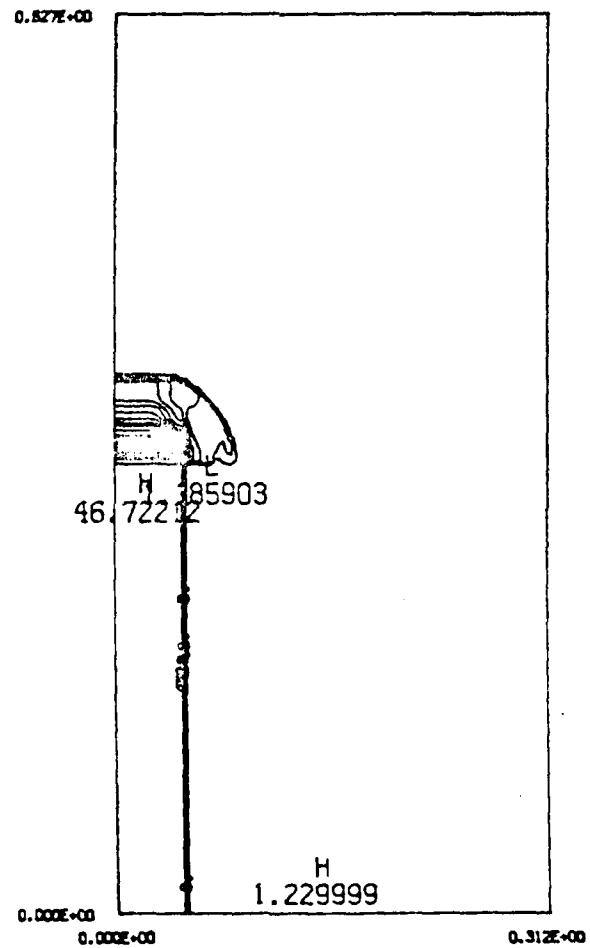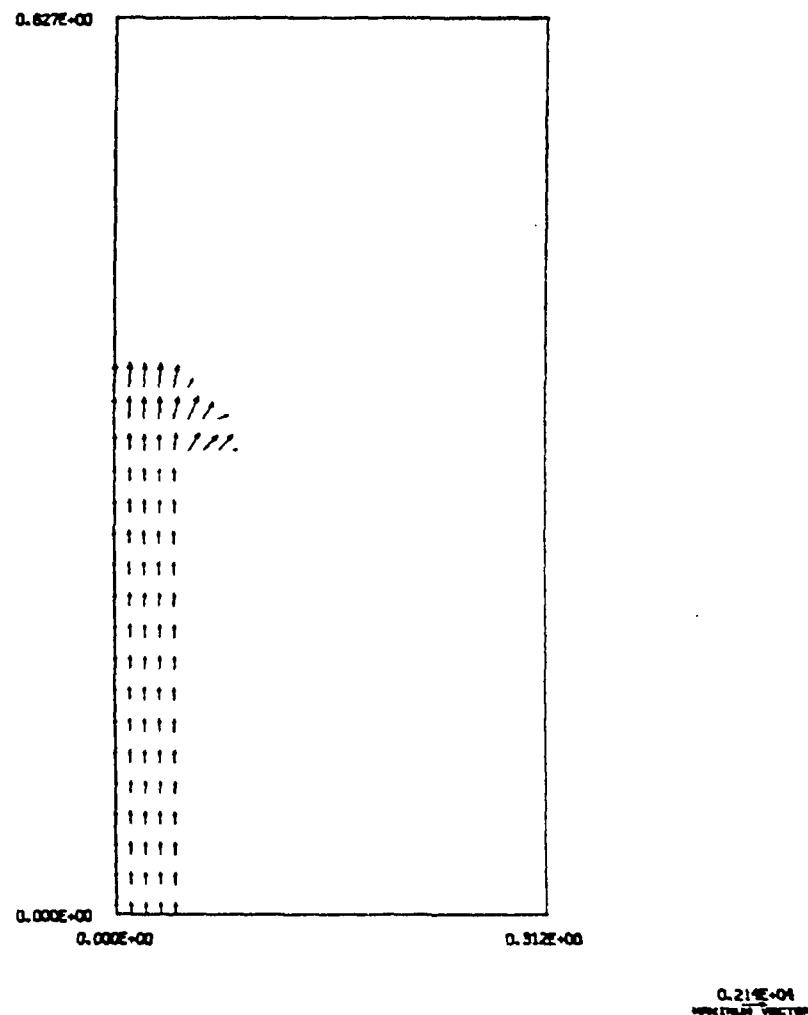
0.627E+00

0.000E+00
0.000E+00   0.312E+00

0.214E+04
MAXIMUM VECTOR

Figure 34d

105 MM HØWITZER MUZZLE FLØW

TIME= 0.50452E-04 SEC.. STEP 143. DUMP HØWZ0002   PRESSURE.NEWTØNS/M==2

CONTØUR FRØM 0.00000   TØ 0.29000E+08 CONTØUR INTERVAL ØF 0.10000E+07 PT(3.3)= 0.29100E+08 LABELS SCALED BY 0.10000E-04

Figure 35a

88

105 MM HØWITZER MUZZLE FLØW

TIME= 0.50452E-04 SEC.. STEP 143. DUMP HØWZ0002   DENSITY 1. KG/M3
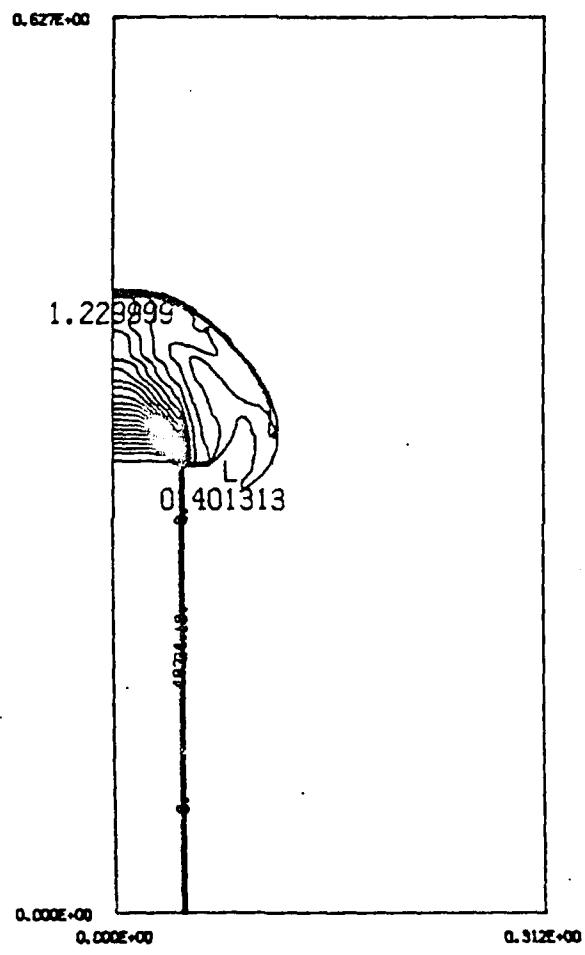
Figure 35b

105 MM HOWITZER MUZZLE FLOW

TIME= 0.50452E-04 SEC.. STEP 143. DUMP HOWZ0002   MACH NUMBER
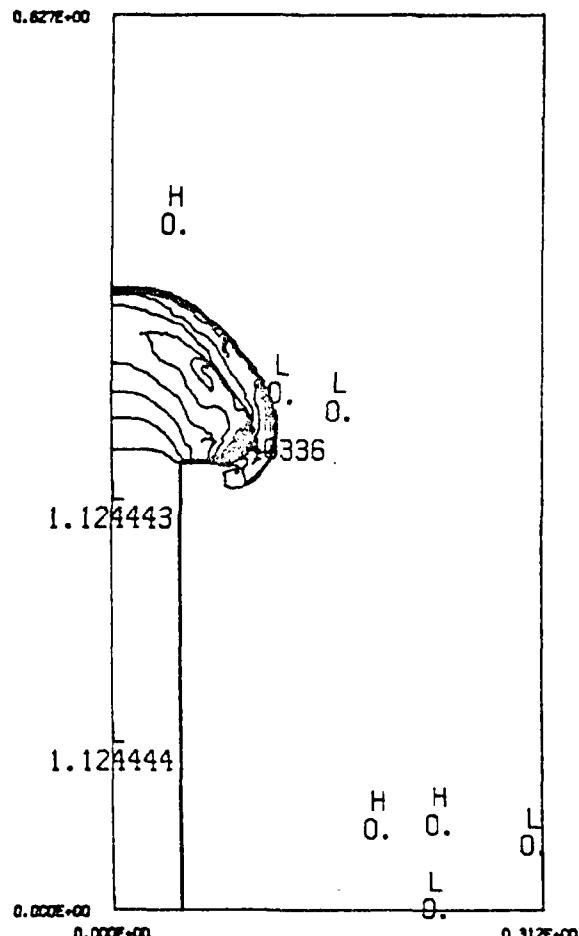
CONTOUR FROM 0.00000   TO 7.2000   CONTOUR INTERVAL OF 0.40000   PT(3.3)= 1.1244

Figure 35c

105 MM HOWITZER MUZZLE FLOW

TIME= 0.50452E-04 SEC., STEP 143, DUMP HOWZ0002   VELOCITY, M/SEC


Figure 35d

105 MM HØWITZER MUZZLE FLØW

TIME= 0.10006E-03 SEC., STEP 253, DUMP HØWZ0003   PRESSURE,NEWTØNS/M**2

Figure 36a

105 MM HØWITZER MUZZLE FLØW

TIME= 0.10006E-03 SEC., STEP 253, DUMP HØWZ0003   DENSITY 1. KG/M3

Figure 36b

AD-A163 332   APPLICATION OF FLUX-CORRECTED TRANSPORT TO TTCP JOINT   2/2
               LAUNCH BLAST COMPUTATIONAL EFFORT(U) NAVAL RESEARCH LAB
               WASHINGTON DC   P S KAMATH ET AL. 31 DEC 85 NRL-MR-5701
UNCLASSIFIED   F/G 19/4   NL

END
FILMED

DTIC
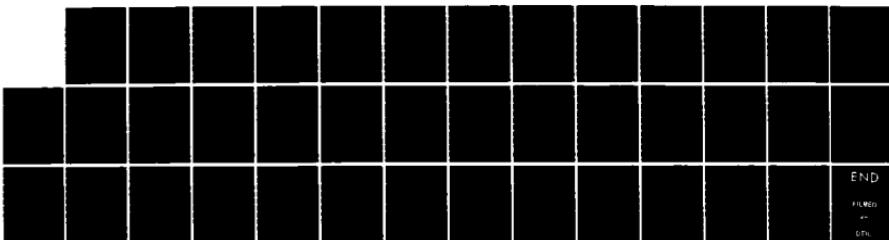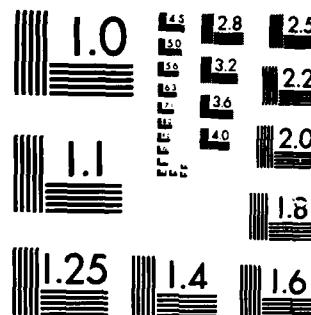
MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

105 MM HØWITZER MUZZLE FLØW

TIME= 0.10006E-03 SEC.. STEP 253. DUMP HØWZ0003   MACH NUMBER

Figure 36c

105 MM HØWITZER MUZZLE FLØW

TIME= 0.10006E-03 SEC.. STEP 253. DUMP HØWZ0003   VELØCITY. M/SEC

Figure 36d

105 MM HOWITZER MUZZLE FLOW

TIME= 0.50000E-03 SEC.. STEP 1433. DUMP HOWZ0005   PRESSURE,NEWTONS/M**2
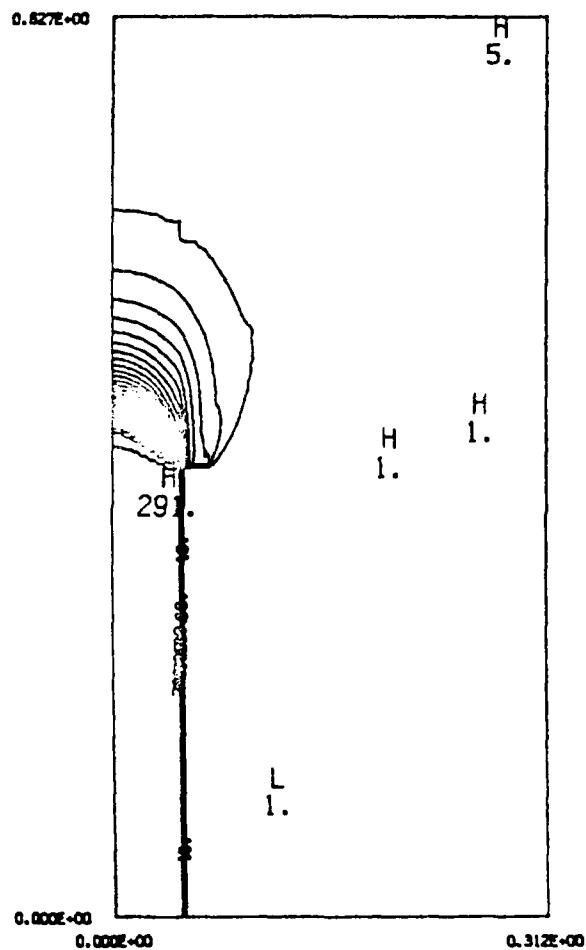
CONTOUR FROM 0.00000 TO 0.28000E+08 CONTOUR INTERVAL OF 0.10000E+07 PT(8,3)= 0.29100E+08 LABELS SCALED BY 0.10000E-04

Figure 37a

105 MM HOWITZER MUZZLE FLOW

TIME= 0.50000E-03 SEC.. STEP 1433. DUMP HOWZ0005   DENSITY 1. KG/M3
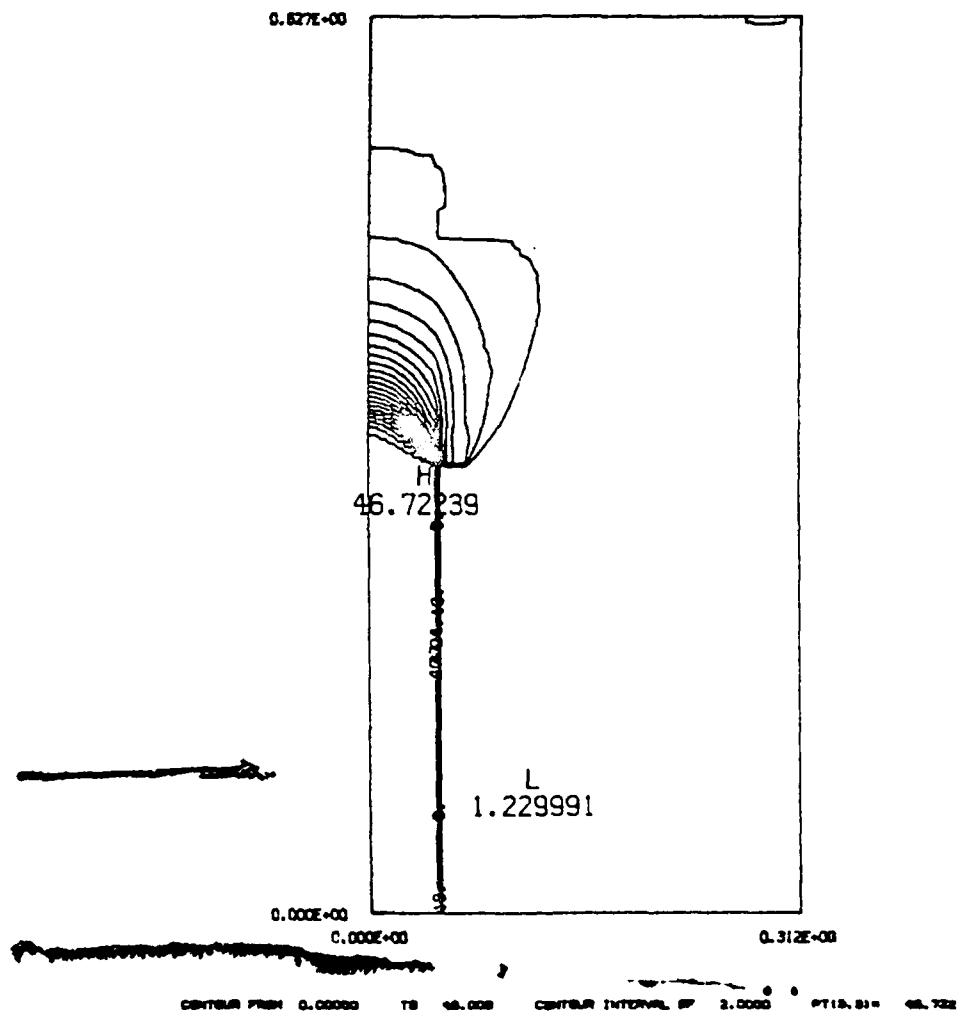
Figure 37b
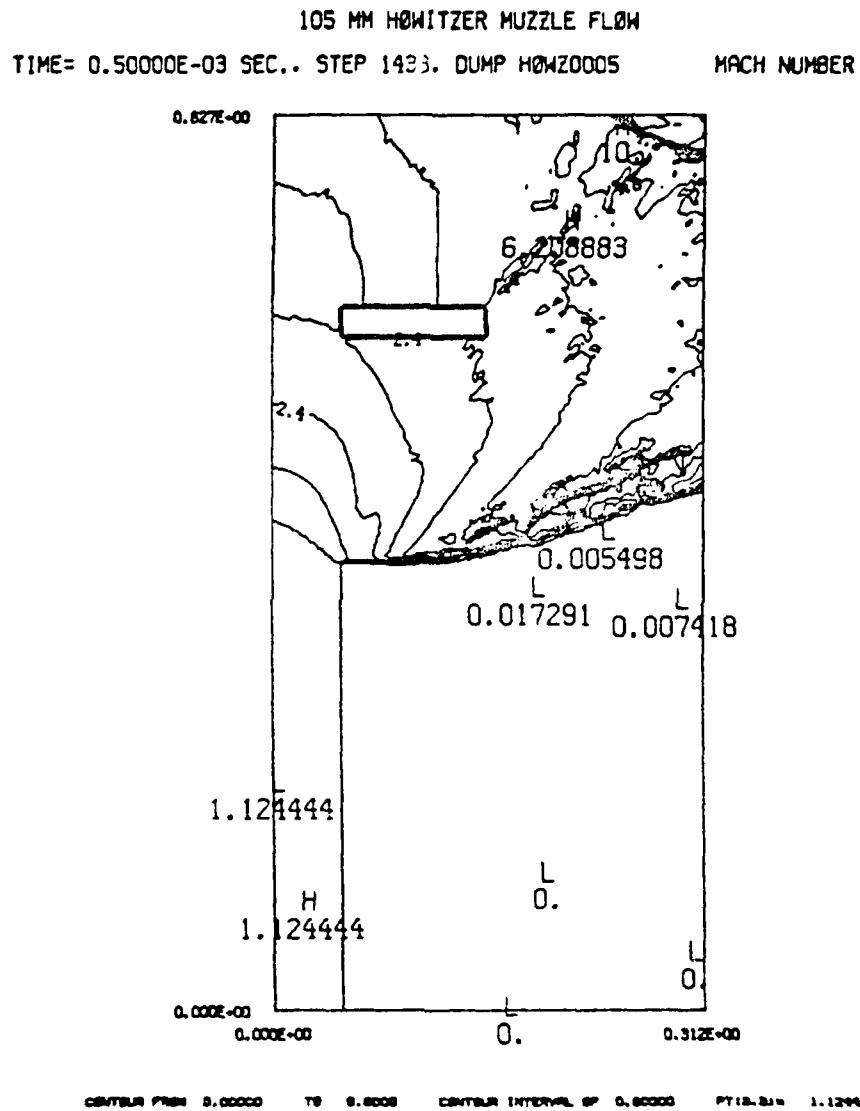
97

105 MM HØWITZER MUZZLE FLØW

TIME= 0.50000E-03 SEC.. STEP 1433. DUMP HØWZ0005   MACH NUMBER

Figure 37c

98

105 MM HOWITZER MUZZLE FLOW

TIME= 0.50000E-03 SEC., STEP 1433, DUMP HOWZO005   VELOCITY.   M/SEC
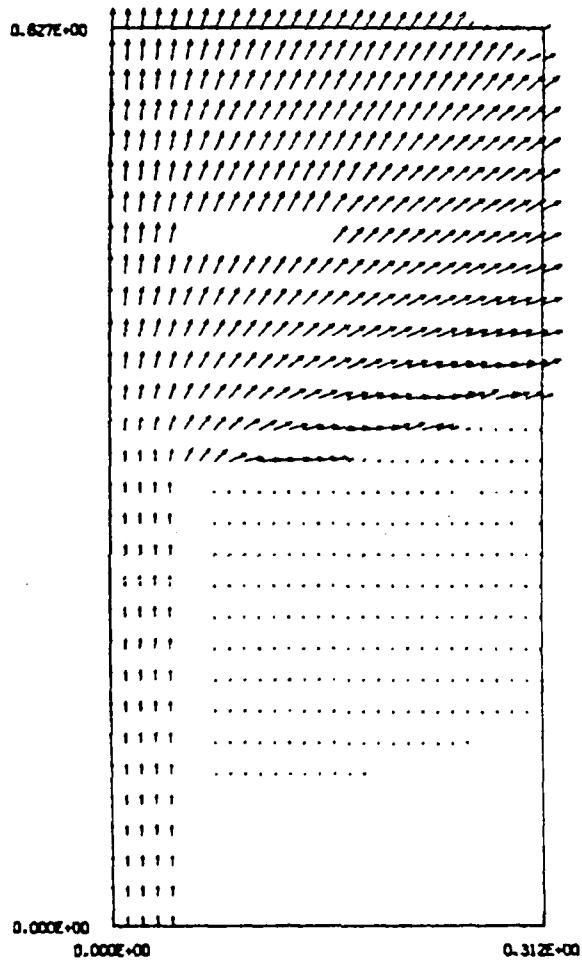
Figure 37d

105 MM HOWITZER MUZZLE FLOW

TIME= 0.10000E-02 SEC., STEP 2735. DUMP HOWZ0007   PRESSURE,NEWTONS/M**2
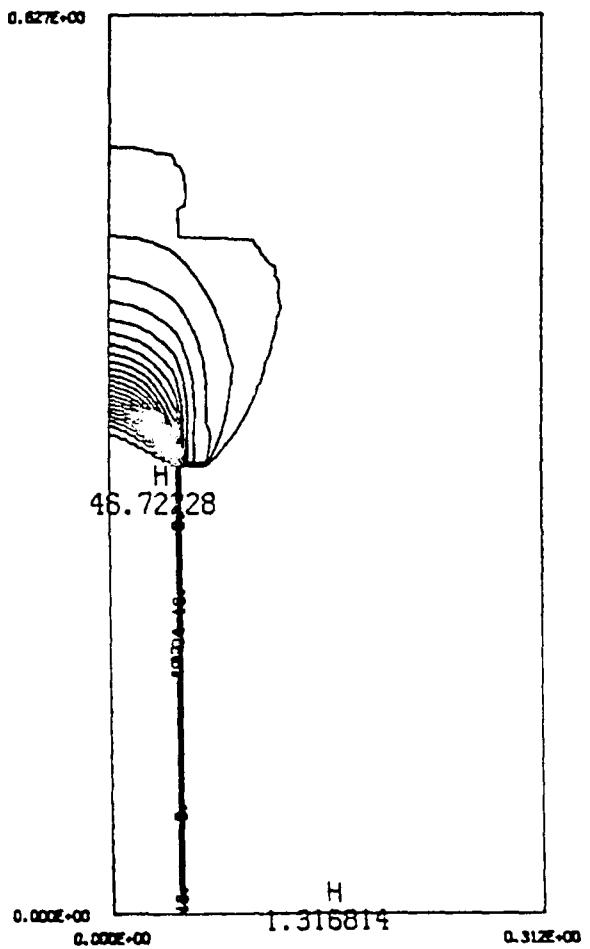
Figure 38a

105 MM HØWITZER MUZZLE FLØW

TIME= 0.10000E-02 SEC., STEP 2735, DUMP HØWZ0007   DENSITY 1. KG/M3

Figure 38b

105 MM HØWITZER MUZZLE FLØW

TIME= 0.10000E-02 SEC., STEP 2735. DUMP HØWZ0007   MACH NUMBER

0.827E+00

5.39.756

2.4

4.454010

L
0.175131

H
1.124444
L
1.124444

L
0.003006

0.000E+00

0.000E+00   0.312E+00

CØNTØUR FRØM 0.00000   TØ 6.8000   CØNTØUR INTERVAL ØF 0.60000   PT(3-31= 1.1244
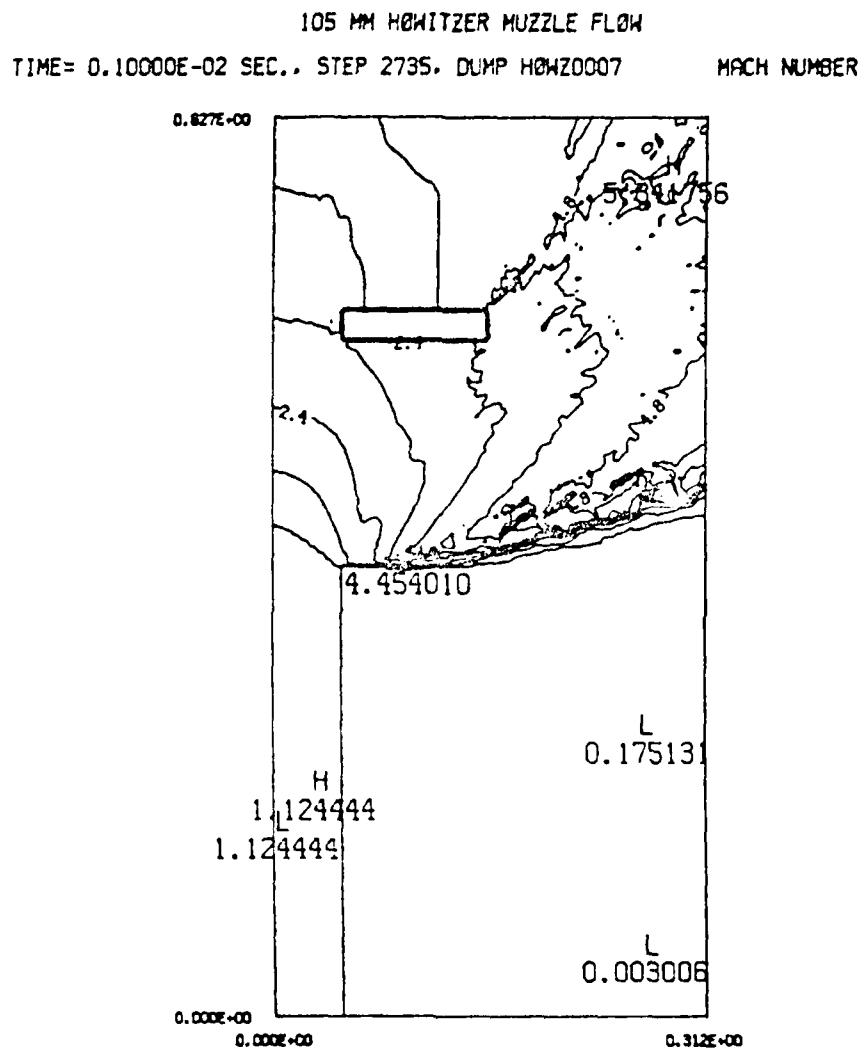
Figure 38c

105 MM HØWITZER MUZZLE FLØW

TIME= 0.75002E-03 SEC., STEP 2073. DUMP HØWZ0006   VELØCITY. M/SEC

Figure 38d

103

STATIØN 1, XS,YS= 0.787E-01 0.466E+00 M

105 MM HØWITZER MUZZLE FLØW

9 DUMPS. LAST DUMP IS HCHIC009

Figure 39a

104

STATIØN 1, XS,YS= 0.787E-01 0.466E+00 M

105 MM HØWITZER MUZZLE FLØW

9 DUMPS, LAST DUMP IS HØWZ0009

Figure 39b

105

STATIØN 1. XS,YS= 0.787E-01 0.456E+00 M

105 MM HØWITZER MUZZLE FLØW

Figure 39c

STATIØN 2, XS,YS= 0.105E+00 0.466E+00 M

105 MM HØWITZER MUZZLE FLØW

Figure 40a

107

STATIØN 2. XS,YS= 0.105E+00 0.466E+00 M

105 MM HØWITZER MUZZLE FLØW

9 DUMPS. LAST DUMP IS H9WZDOO9

Figure 40b

108

STATIØN 2. XS.YS= 0.105E+00 0.466E+00 M

105 MM HØWITZER MUZZLE FLØW

8 DUMPS. LAST DUMP IS HGWZ0009

Figure 40c

STATION 3. XS.YS= 0.131E+00 0.466E+00 M

105 MM HØWITZER MUZZLE FLØW

9 DUMPS. LAST DUMP IS HØWZ0009

Figure 41a

110

STATIØN 3. XS,YS= 0.131E+00 0.466E+00 M

105 MM HØWITZER MUZZLE FLØW

9 DUMPS, LAST DUMP IS HØWZ0009

Figure 41b

111

STATIØN 3. XS.YS= 0.131E+00 0.466E+00 M

105 MM HØWITZER MUZZLE FLØW

8 DUMPS. LAST DUMP IS HØWZ0009

Figure 41c

112

STATIØN 4. XS.YS= 0.151E-02 0.525E+00 M

105 MM HØWITZER MUZZLE FLØW

9 DUMPS. LAST DUMP IS HØWZ0009

Figure 42a

113

STATIØN 4, XS,YS= 0.151E-02 0.525E+00 M

105 MM HØWITZER MUZZLE FLØW

8 DUMPS, LAST DUMP IS HØWZ0009

Figure 42b

114

STATIØN 4, XS,YS= 0.151E-02 0.525E+00 M

105 MM HØWITZER MUZZLE FLØW

8 DUMPS, LAST DUMP IS H9WZ0009

Figure 42c

115

STATIØN 5. XS.YS= 0.105E+00 0.497E+00 M

105 MM HØWITZER MUZZLE FLØW

8 DUMPS. LAST DUMP IS H3HZ0008

Figure 43a

116

STATION 5. XS.YS= 0.105E+00 0.497E+00 M

105 MM HØWITZER MUZZLE FLØW

9 DUMPS. LAST DUMP IS HØWZ0009

Figure 43b

117

STATION 5. XS.YS= 0.105E+00 0.497E+00 M

105 MM HOWITZER MUZZLE FLOW

8 DUMPS. LAST DUMP IS HOWZ0009

Figure 43c

118

STATION 6. XS.YS= 0.182E+00 0.415E+00 M

PRESSURE,NEWTONS/M∗∗2

14×10⁵
13×10⁵
12×10⁵
11×10⁵
10×10⁵
9×10⁵
8×10⁵
7×10⁵
6×10⁵
5×10⁵
4×10⁵
3×10⁵
2×10⁵
10⁵
0

0 .0001 .0002 .0003 .0004 .0005 .0006 .0007 .0008 .0009 .0010 .0011

TIME, SEC.

105 MM HOWITZER MUZZLE FLOW

9 DUMPS. LAST DUMP IS HOWZC009

Figure 44a

119

STATIØN 6. XS,YS= 0.182E+00 0.415E+00 M

105 MM HØWITZER MUZZLE FLØW

9 DUMPS. LAST DUMP IS HB-Z0009

Figure 44b

STATIØN 6. XS.YS= 0.182E+00 0.415E+00 M

105 MM HØWITZER MUZZLE FLØW

9 DUMPS. LAST DUMP IS HØWZ0009

Figure 44c

121

STATIØN   7. XS.YS= 0.210E+00 0.315E+00 M

105 MM HØWITZER MUZZLE FLØW

9 DUMPS. LAST DUMP IS HØWZD009

Figure 45a

122

STATIØN 7. XS.YS= 0.210E+00 0.315E+00 M

105 MM HØWITZER MUZZLE FLØW

8 DUMPS. LAST DUMP IS H0HZDC09

Figure 45b

123

STATIØN 7. XS.YS= 0.210E+00 0.315E+00 M

105 MM HØWITZER MUZZLE FLØW

9 DUMPS. LAST DUMP IS HØWZ0009

Figure 45c

124

STATIØN 8. XS,YS= 0.182E+00 0.210E+00 M

105 MM HØWITZER MUZZLE FLØW

9 DUMPS. LAST DUMP IS HØWZC009

Figure 46a

STATIØN 8. XS.YS= 0.182E+00 0.210E+00 M

105 MM HØWITZER MUZZLE FLØW

8 DUMPS. LAST DUMP IS H3HZ0003

Figure 46b

126

STATIØN 8. XS,YS= 0.182E+00 0.210E+00 M

105 MM HØWITZER MUZZLE FLØW

8 DUMPS. LAST DUMP IS HØWZ0009

Figure 46c

127

STATIØN 9, XS.YS= 0.105E+00 0.133E+00 M

105 MM HØWITZER MUZZLE FLØW

9 DUMPS. LAST DUMP IS HØWZ0009

Figure 47a

128

STATION 9. XS.YS= 0.105E+00 0.133E+00 M

105 MM HOWITZER MUZZLE FLOW

9 DUMPS. LAST DUMP IS HH2000B

Figure 47b

129

STATIØN 9. XS.YS= 0.105E+00 0.133E+00 M

105 MM HØWITZER MUZZLE FLØW

8 DUMPS. LAST DUMP IS HØ+200CR

Figure 47c

130

Figure 48

RFM Parallel Benchmark

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